

Understanding Sea Level Rise: The Roles of Coupled Systems

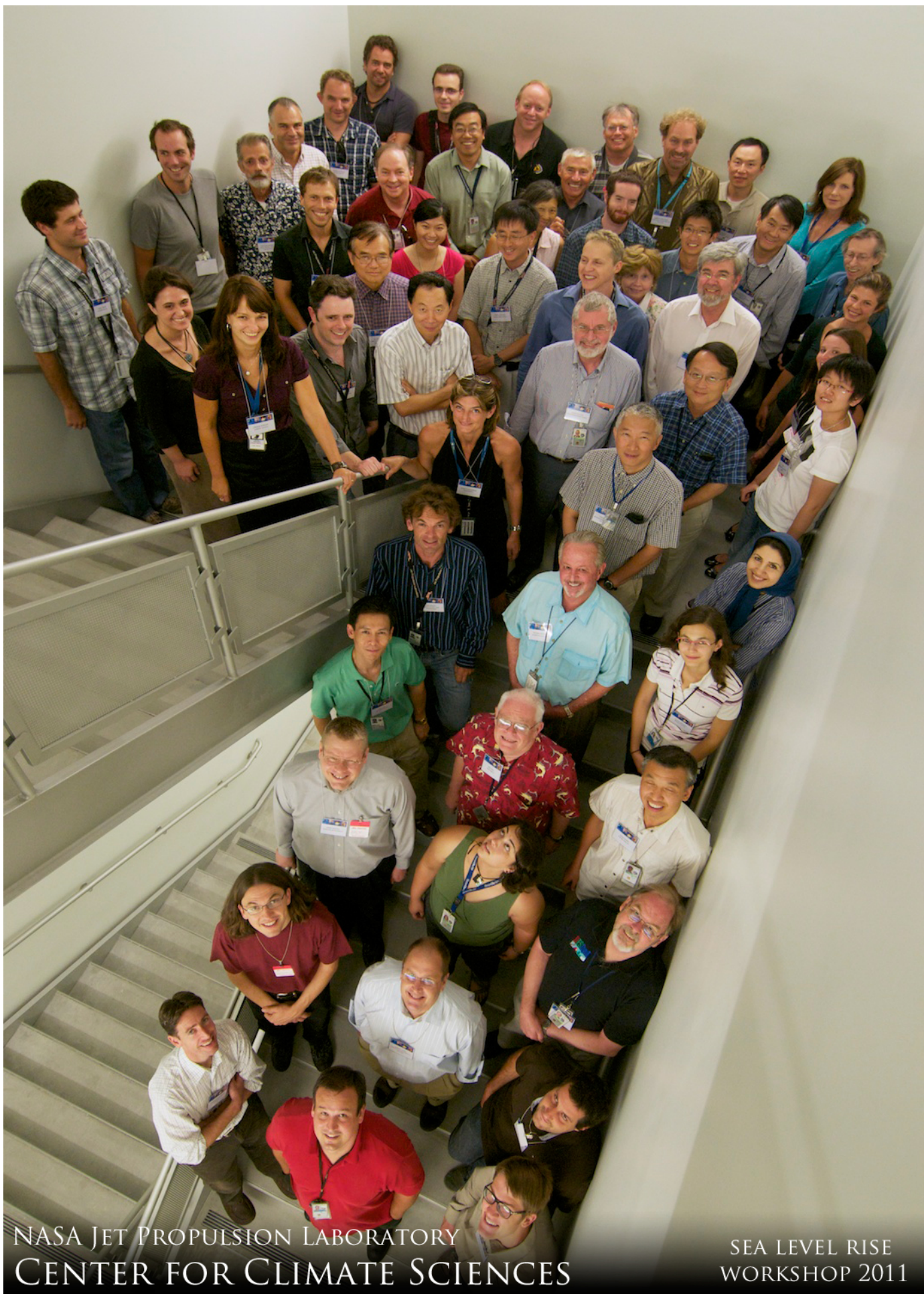
A Workshop on the Evaluation, Enhancement & Importance of Sea Level Change Research at the NASA Jet Propulsion Laboratory (JPL)

Proceedings & Actions Summary
29-31 August 2011
Jet Propulsion Laboratory, Pasadena, CA



By how much will sea level rise during the 21st Century?

Sponsored by the JPL Center for Climate Sciences



NASA JET PROPULSION LABORATORY
CENTER FOR CLIMATE SCIENCES

SEA LEVEL RISE
WORKSHOP 2011

I. Table of Contents

II. Introduction.....	5
III. Session Summaries	5
A. Session 1: The State of Sea level Change Research	5
B. Session 2: Sea Level & Air-Sea Interaction	9
C. Session 3: Sea Level & the Cryosphere	13
D. Session 4: Sea Level, the Solid Earth & Geodesy	17
E. Session 5: Regional Sea Level Change.....	21
F. Session 6: JPL and The Way Forward.....	24
IV. Enhancement of Sea Level Research and Collaborations at JPL	27
A. Importance of NASA-JPL Satellite Missions in Understanding Sea Level Rise.....	27
B. Efforts to Enhance Understanding of Ice Sheets and Ice-Ocean Interactions	29
C. Downscaling Effort to Tackle Regional Sea Level Change.....	30
D. Collaboration with the US Navy	32
V. Societal Need and Practicability	33
A. Sea Level Seminar	33
B. Student Art Exhibit	35
C. SLR & Decision-makers	36
VI. References.....	39

Executive Summary

Global sea level rise is one of the most socially relevant consequences of human caused global warming. On August 29-31, 2011, the Jet propulsion Laboratory (JPL) Center for Climate Sciences (CCS) sponsored an internal workshop for JPL community members and their collaborators. The workshop highlighted JPL's history of contributing to groundbreaking findings in sea level research through major technological advances in satellite development. The goal of the workshop was to develop a strategy for the advancement of sea level research at JPL, and within NASA as a whole.

The workshop opened cross-disciplinary dialog among JPL scientists, and focused primarily on the interdisciplinary aspects of sea level research and those aspects that JPL is best suited to address. The workshop achieved three primary outcomes that addressed the workshop goal. These were:

- (1) A concise list of **major science priorities** that JPL is particularly well-suited to address in the near future were identified
- (2) A **conceptual map was developed to illustrate how different satellite and airborne missions, climate modeling efforts and data analysis projects taking place across NASA-JPL relate to one another in the context of sea level research**, and how these components can work in sync to streamline progress toward improved sea level estimation and projection
- (3) **New internal and inter-institutional collaborative efforts** involving JPL researchers in different disciplines were conceived

The path forward was identified and articulated by the meeting participants at the workshop and in the weeks that followed. This path must include continued support for existing and upcoming missions like the Jason and GRACE series, which constitute an early warning system for rapid acceleration of future sea level rise, as well as planned and potential future missions like SWOT, IceSat II, GRASP and OASIS, which may lay the groundwork for realistic predictions of sea level rise. Research programs that include analysis and modeling efforts must also be supported, with a particular emphasis on ice sheet modeling, ocean-ice interactions and regional downscaling. JPL has strong existing assets in these domains, but continued coordination, management and support will be needed to realize their potential impact on sea level rise research. Finally, potential collaborations with the Navy and development of decision support capabilities may also play important roles in the development of a robust sea level research program at JPL and across NASA.

II. Introduction

Global sea level rise and regional sea level change are both imminent and socially relevant consequences of human caused climate change. Sea level is influenced by many components of Earth's climate system (the atmosphere, hydrosphere, cryosphere and lithosphere) and by how interactions between these components evolve over time. On August 29-31, 2011, the Jet Propulsion Laboratory (JPL) Center for Climate Sciences (CCS) sponsored an internal workshop for JPL community members and their collaborators, centered on the issue of sea level rise linked to climate change. The goal of the workshop was to develop a strategy for the advancement of sea level research at JPL, and within NASA as a whole. It focused primarily on the interdisciplinary aspects of sea level research and those aspects that JPL is best suited to address.

Over 100 researchers from roughly 10 independent disciplines, and numerous levels of JPL and NASA management, participated. The meeting format consisted of 6 general topic sessions, which included a combination of invited oral presentations and open discussions presided over by a panel of experts in the given topic area. Additionally, a poster session gave researchers from all disciplines and levels of experience a chance to showcase their own work. Extensive time for guided but open discussions was used to highlight research that could be significantly advanced by establishment of new cross-disciplinary collaborations.

This document summarizes content and panel recommendations from each of the 6 topic area sessions. It also features some of the new collaborations and activities that have evolved out of the session discussions since the sea level workshop (hereafter, SLW-2011). The last section includes a report on the level of societal need for what NASA, and JPL in particular, has to offer in this area, and the practicability of future efforts.

III. Session Summaries

A. Session 1: The State of Sea level Change Research

The objective of the first session was to assess the current state of sea level research and to identify/highlight potential avenues of future research. It began with an introduction by Eric Lindstrom (NASA Science Mission Directorate Program Scientist, NASA Physical Oceanography Program Lead, co-Chair of the Interagency Working Group on Ocean Partnerships, and Chairman of the International Ocean Observations

Panel for Climate (OOPC)), followed by three keynote lectures spanning the topic areas covered in the remainder of the workshop. Speakers included John Church (Commonwealth Scientific and Industrial Research Organization (CSIRO) Centre for Australian Weather and Climate Research), Eric Rignot (JPL and University of California at Irvine, UCI) and Mark Tamisiea (National Oceanography Center (NOC), Liverpool, UK).

Eric Lindstrom opened the workshop with an overview of what he sees as the role of NASA/JPL in sea level research. While NASA has great strengths in providing a global perspective from space, as well as experience dealing with complex problems involving considerable unknowns, it can be disconnected from “customers” and the application community for sea level information. Additionally, the continuity of key data sets is not assured. He posed these challenges as opportunities for collaboration with partner agencies (e.g., National Oceanographic and Atmospheric Administration (NOAA) and the United States Geological Survey (USGS)), and expressed the importance of continuity of key satellite missions, such as the Jason altimeter series, GRACE and its follow-on projects, ICESAT-2, etc. He expressed that with these aspects in place, NASA/JPL would be well-situated for moving sea level research to the next level, allowing the research community to question what we think we already know, while delving into what remain great unknowns. This sentiment set the tone for the remainder of the workshop.

John Church’s talk addressed the general state of sea level research and the challenges for improving projections of sea level rise for the 21st Century and beyond. He noted that urban development in coastal regions has enjoyed relative stability of sea level for most of the past 2000 years, and that the last interglacial period (approximately 125,000 years ago) exhibited global sea levels of at least 6 meters higher than today. Evidence for accelerated sea level rise during the 20th century and a closed sea level budget for the period since the 1970s were also presented. Church also discussed the challenges in projecting each component of sea level rise. For example, the coupled climate system models used for the Intergovernmental Panel on Climate Change (IPCC) Fourth Assessment Report (AR4) did a reasonably good job of capturing sea level rise due to thermal expansion, however, it is necessary to include aerosol forcing, in addition to greenhouse gas forcing, for proper simulation of cloud and radiative transfer processes and feedbacks. Most models still mix heat in the atmosphere too deeply. Glaciers apart from Greenland and Antarctica remain poorly observed, but are estimated to contribute approximately half of the modern non-thermohaline (non-density related) rate of sea level rise due to melting land ice, with the Greenland and Antarctic ice sheets contributing the other half. Meanwhile, the response of the polar ice sheets to climate change remains the largest cause of uncertainty in future rates of sea level rise. Projections of sea level rise must consider regional effects caused by changes in ocean circulation, geodetic fingerprints of ice loss in the ice sheets, as well as changes in wave height, which are critical for local impacts. Research priorities for meeting the challenge of improving projections were discussed. These included maintaining and extending the

observing systems for sea level change and its components (altimetry, tide gauges, satellite and *in situ* temperature and salinity observations, etc.) as well as improving the paleoclimate record for the last inter-glacial period and the Holocene. Glacier, ice sheet and terrestrial water mass storage observations must continue (including time-variable gravity). Modeling efforts must be advanced to include all contributions and to improve understanding of ice sheet dynamics. Regional sea level variations must be explained (and eventually projected) to allow for detection and attribution of observed patterns of sea level change. Lastly, probabilistic projections are needed that use all sources of information (paleoclimate/proxy data, semi-empirical and physical models), along with risk assessments on a variety of timescales.

Eric Rignot discussed the current mass balance of the Greenland and Antarctic ice sheets, the processes through which they lose mass, and the different techniques used to measure mass loss: Gravity Recovery and Climate Experiment (GRACE) satellite estimates, altimetry, and a technique known as the flux method (Rignot and Thomas 2002). He described each approach, their advantages and disadvantages, and the convergence of each approach in assessing the sea level rise contributed by polar ice sheets. The net annual mass loss of both ice sheets combined is thought to contribute to sea level rise at a rate of approximately 2 mm per year. More importantly, he also discussed the increasing trend in mass loss, with a cumulated acceleration extrapolated to $-36.2 \pm 2 \text{ Gt/yr}^2$ for Greenland and Antarctica, as well as the differences between Greenland and Antarctica. Mass loss in Antarctica is not from surface melting, but rather from melting under the ice shelves (~50%) and calving of icebergs. In Greenland, the situation is reversed, with surface melting accounting for the bulk of the mass loss through water runoff at the calving fronts of glaciers. Processes involved in mass changes on both continents vary widely. In Greenland, ice-ocean interactions at the calving fronts of grounded glaciers are essential, with fjord bathymetry being one of the main unknowns in constraining the ocean circulation. In Antarctica, ice-ocean interactions also play a critical role, although the emphasis is on melting under ice shelves near the grounding line. Once more, bathymetry under the ice shelf is critical in understanding penetration of warm water to the base of grounded glaciers and ice streams.

Rignot also emphasized ocean warming itself as an important process driving the ice loss. These results are consistent across different types of observations. Rignot concluded by charging the scientific community with three challenges: 1) improve and expand observations to constrain models, such as ice thickness, surface thermal forcing and ocean thermal forcing; 2) improve understanding of two key processes, ice-ocean interactions and basal sliding; 3) place more emphasis on numerical models, remote sensing and data assimilation. The road map for meeting these challenges involves: 1) interdisciplinary science, 2) ship-borne surveys and Argo floats at the periphery of Greenland and Antarctica, 3) solid NASA satellite/observation programs for ice mass loss (gravity), ice motion (Interferometric Synthetic Aperture Radar (InSAR); see Figure 1), ice thickness, volume changes (altimetry); 4) more Unmanned Airborne Vehicle

(UAV) technology, auto-submarines, gliders to supplement satellite data below the surface, 5) advanced coupled numerical models constrained by a network of sensor observations.

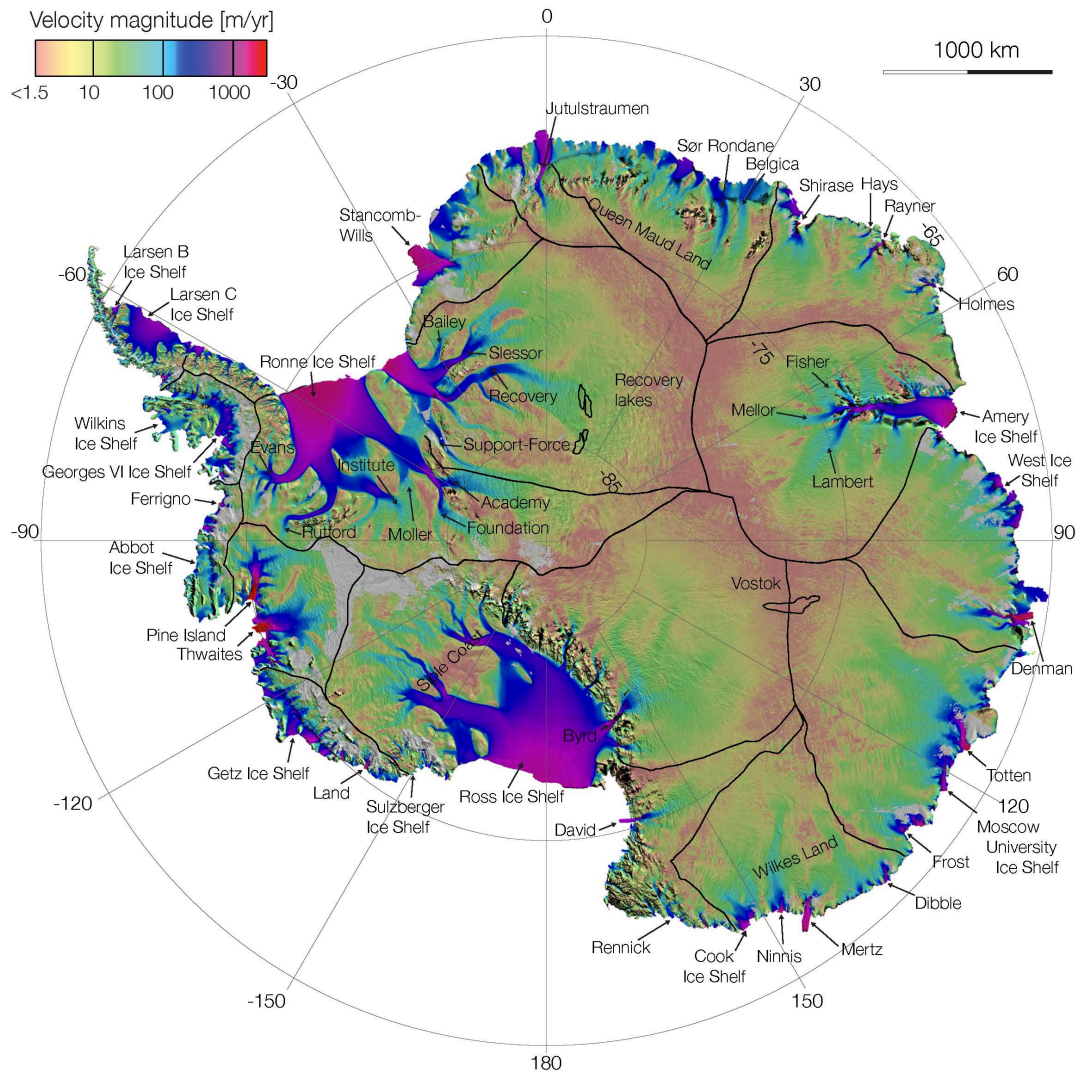


Figure 1: First complete map of ice motion in Antarctica reveals widespread, patterned, enhanced flow with tributary glaciers reaching hundreds to thousands of kilometers inland. This view of ice sheet motion emphasizes the importance of basal-slip ice motion over deformation-dominated motion, with far reaching implications for the prediction of ice sheet evolution. From Rignot et al. (2011).

Mark Tamisiea discussed the role of the solid earth and geodesy in sea level change. Tamisiea explained the basic non-oceanographic mechanisms that drive contemporary sea level change. These include land motion that occurs quickly (i.e., elastic rebound of the Earth's crust due to modern-day unloading of ice) and motion that is essentially secular (viscous flow of the mantle in response to the disappearance of the ice sheets between 10 and 20 thousand years ago). In addition, changes in the gravity field and

shifts in the direction of Earth's rotational axis redistribute water and result in regional sea level changes. All of these effects must be modeled and accounted for in order to properly interpret modern day observations from gravity satellites, tide gauges and satellite altimeters. Future projections of sea level change due to ice loss from the continents will also require modeling of solid Earth contributions, as these changes will be very non-uniform and will become increasingly important as ice loss begins to account for a larger portion of global sea level change. These topics are discussed in more detail in section II D.

B. Session 2: Sea Level & Air-Sea Interaction

Session 2 addressed aspects of sea level research linked specifically to air-sea interactions and ocean processes. Presentations were given by 5 JPL-based speakers, and keynote speaker, John Church, joined the expert panel for subsequent discussion.

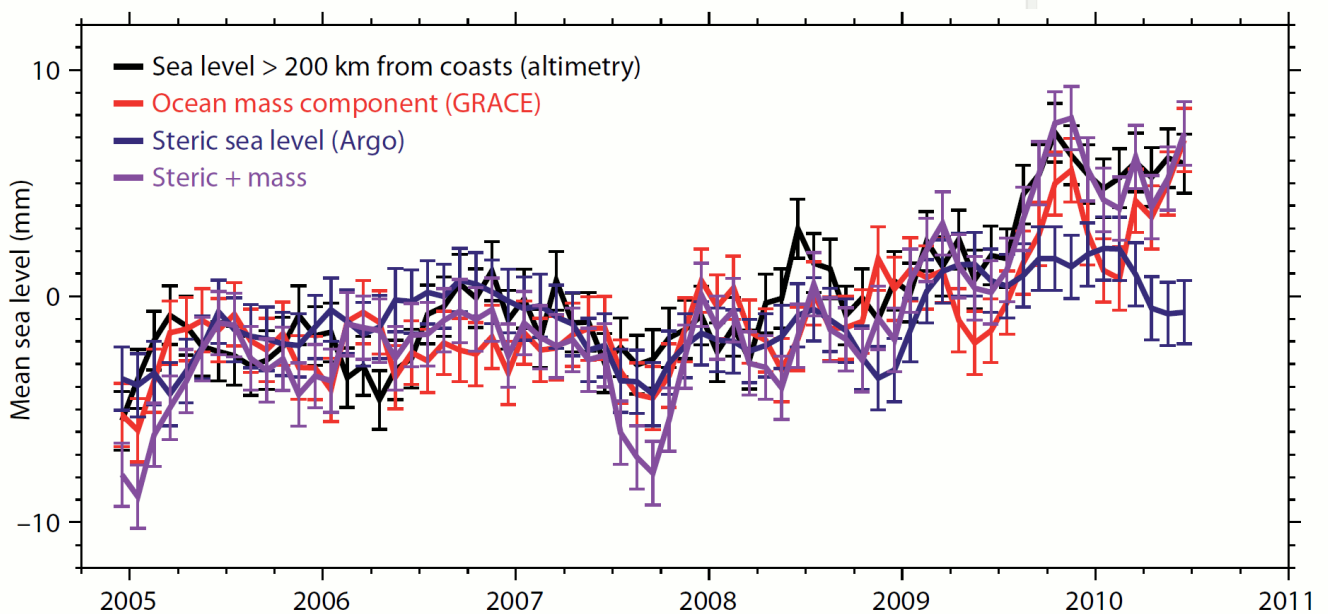


Figure 2: Monthly estimates from Jason-1 and Jason-2 of global mean sea level for areas greater than 200 km from the coast (black), which are in general agreement with the sum (purple) of the ocean mass component from the Gravity Recovery and Climate Experiment, GRACE (red), and the steric component of the upper 900 m from Argo (blue). Seasonal signals have been removed and smoothed with a three-month running mean. The error bars are one standard error. From Leuliette and Willis (2011).

Josh Willis (Jason-3 Project Scientist) discussed observations of sea level rise and its different contributing elements. In particular, global mean sea level rise is due to additional heat and mass in the ocean. Satellite altimetry, Argo floats and GRACE (satellite gravity measurements) allow closure of the sea level budget within their

uncertainties on seasonal to interannual to decadal time scales. For instance, during 1993 to 2010, sea level contributions measured by these three instrument types rose at a rate of 3.1, 0.8, and 2.1 mm/year, respectively (e.g., Figure 2). Recent advances will further improve the fidelity and accuracy of the estimates, such as additional bias corrections in XBT data that would allow for enhanced accuracy in the historical record. In addition to global mean trends, Willis also showed regional trends largely reflecting thermosteric (density related) changes as opposed to mass changes. Global mean sea level also has short term changes; a recent drop in global mean sea level in 2010 can be attributed to anomalies in the hydrologic cycle, with excess rain over Australia and the Amazon basin seen by GRACE with corresponding decrease of mass from the ocean.

Timothy Liu described a new way of estimating atmospheric water transport from satellite observations. A humidity-weighted horizontal velocity is empirically derived from scatterometer wind stress at the ocean surface and cloud drift at 850 mbar geopotential height. The velocity's product with column-integrated water vapor defines lateral water transport that closely matches those based on *in situ* measurements. The fidelity of the estimated transport is also demonstrated by its consistency with evaporation minus precipitation estimates over the global ocean. The transport estimates, in turn, provide direct estimates of water transport from the ocean to the land that result in global mean sea level change due to ocean mass changes, consistent with GRACE measurements. Scatterometer winds are no longer available from QuikSCAT but the combined estimate of other scatterometers (ASCAT, Oceansat-2, Haiyang-2) could help resolve the diurnal cycle in wind stress, which would improve the water transport estimate.

Ichiro Fukumori (a co-developer of the JPL Estimating the Circulating and Climate of the Ocean (ECCO) project) discussed the utility of ocean modeling and data assimilation in studying sea level change. In particular, models and assimilation provide effective tools to quantitatively analyze dynamic mechanisms of sea level change that can otherwise be difficult to perform. For instance, geographic variations of sea level change are largely due to redistribution of water with different properties instead of external inputs of heat or mass (e.g. Figure 3). Models are particularly skillful in resolving such changes and in identifying their causal mechanisms (Figure 4). Freshwater input also causes slow regionally varying sea level changes that can be effectively simulated by models, in addition to the fast, globally uniform adjustment. Data assimilation provides a synthesis of often sparse and incomplete observations, and can also correct inaccuracies in estimates of external climate forcings pertinent to sea level rise.

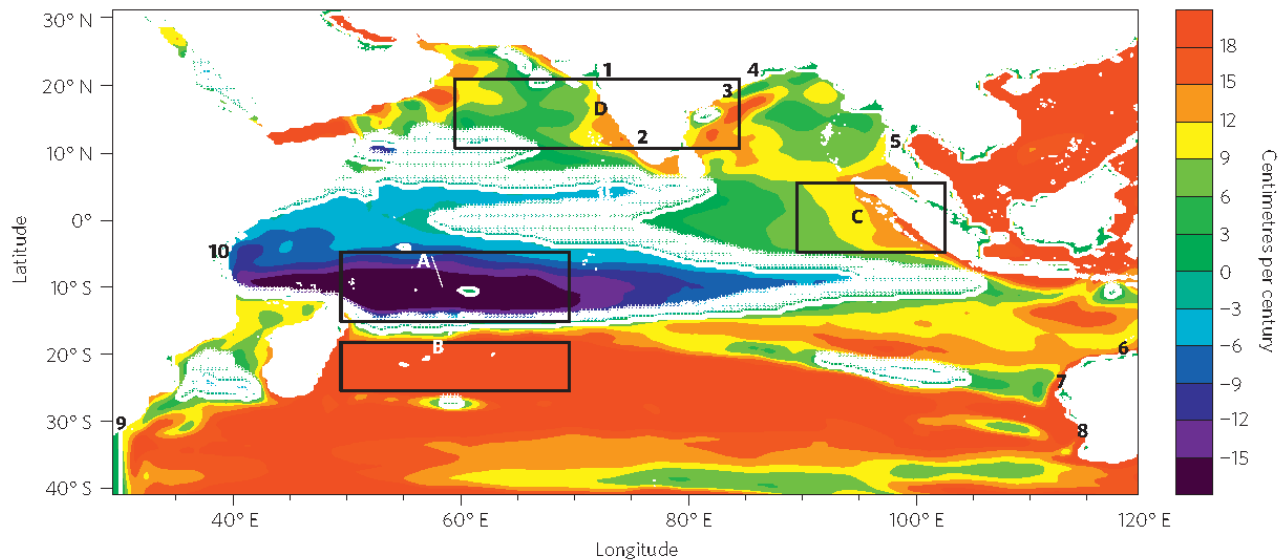


Figure 3: The sea level trend in the Indian Ocean during 1961-2008 simulated by an ocean general circulation model. The variabilities are attributed to water mass redistribution driven by changes in atmospheric circulation (wind), and illustrate the importance of changing ocean circulation on regional sea level change. From Han et al. (2010).

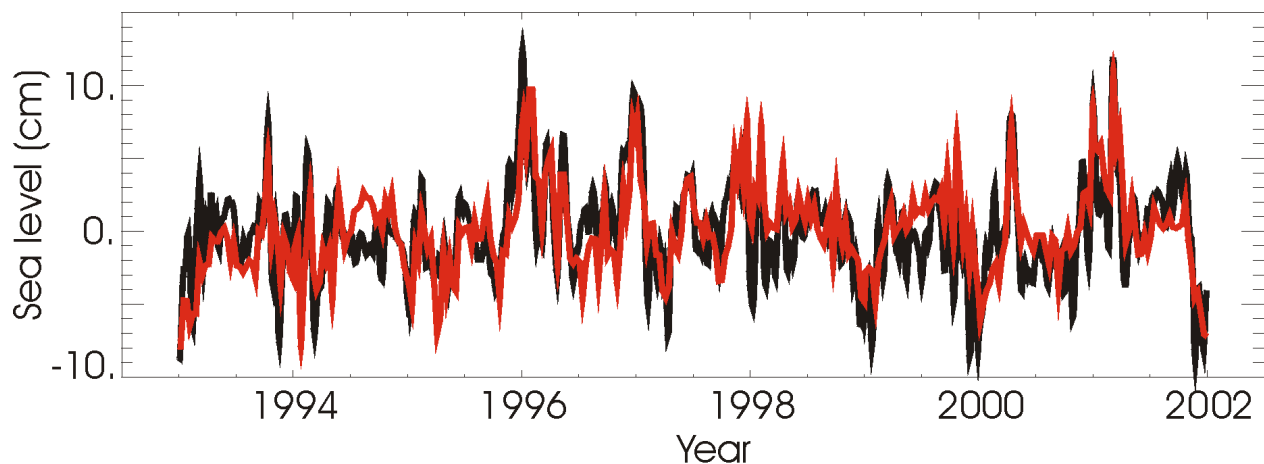
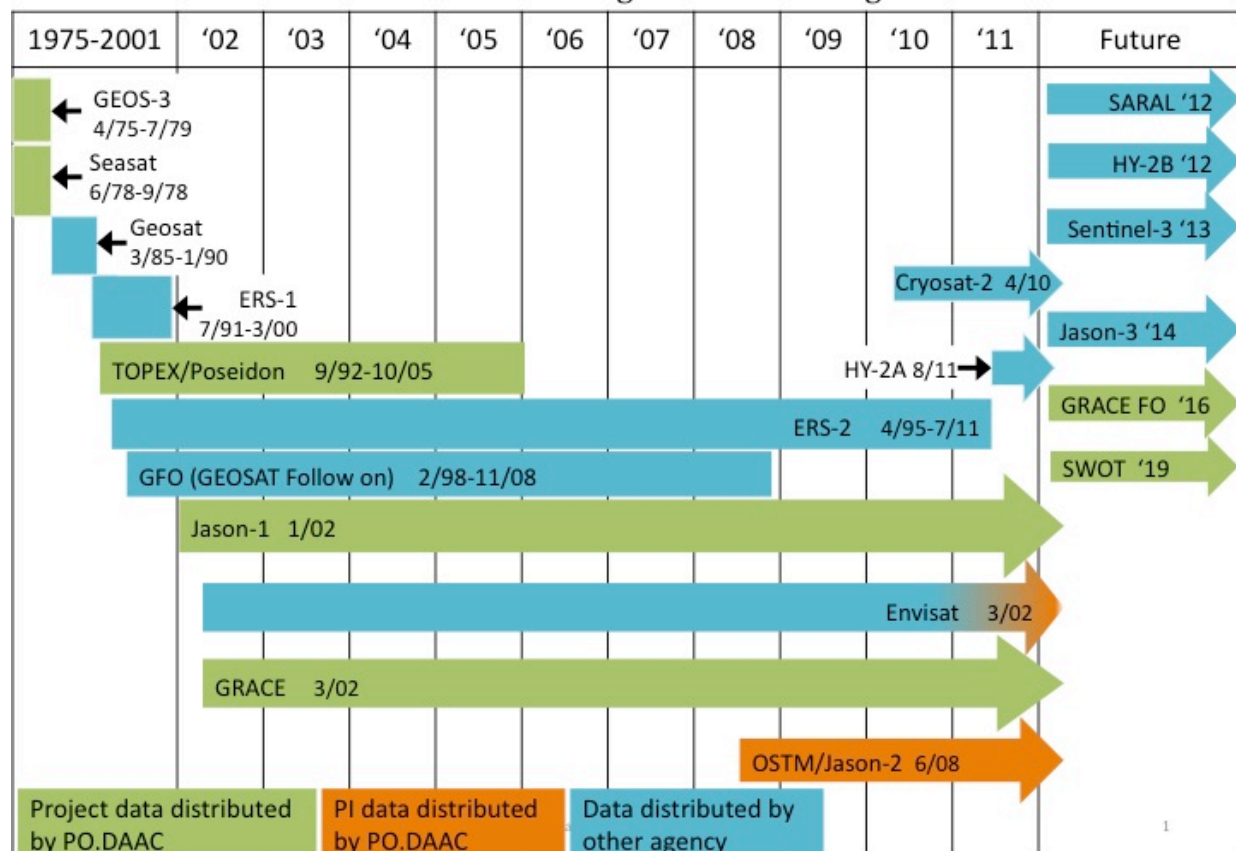


Figure 4: A comparison of mean sea level anomaly in the Mediterranean Sea from altimetric measurements (black) and the ECCO ocean model (red). The consistency between model and data illustrates the fidelity of ocean models in resolving observed variations of sea level. The model's complete physical description of the ocean provides a means to analyze processes controlling the ocean's variability. In this example, the variability, associated with a near-uniform variation of the Mediterranean Sea, was found to be driven to by winds in the vicinity of the Strait of Gibraltar, causing an exchange of mass between the Mediterranean Sea and the North Atlantic Ocean. From Fukumori et al. (2006).

Missions Measuring Sea Surface Height



Oceanographic issues in further advancing sea level research were discussed during an open forum following the presentations. Discussion panelists included keynote speaker Church, and session speakers Willis, Liu and Fukumori. Participants agreed that satellite observations have modernized sea level research. The synergy among the

different types of measurements, especially sea level and gravity, are critical for sea level science. Change in the deep ocean is one of the most urgent observations that need improvement. Efforts to extend Argo floats into the deep ocean are promising. Yet, assuring continuity of the different measurements and translating the requirements into action remain challenging. Where the heat and freshwater that underlie sea level change come from, and how and where they spread in the ocean are some of the central science questions that call for further advancement. Projecting regional sea level rise over the next century is of most interest to society (discussed further in sections III and IV). While models are skillful in simulating past and present regional sea level change, difficulties remain in predicting future changes. The most significant challenge concerns modeling ice sheets. The future behavior of ice sheets is the largest source of uncertainty in the magnitude of sea level rise. While wind-driven changes of the ocean are dominant contributors to regional sea level change on decadal time-scales, melting of ice sheets can dwarf these changes over a century.

C. Session 3: Sea Level & the Cryosphere

Session 3 addressed issues specifically linked to how the cryosphere and ice-air-sea interactions affect sea level. It featured 3 speakers who collectively presented the work of numerous researchers at JPL, UCI and the University of California at Los Angeles (UCLA), currently being conducted as part of a larger interdisciplinary collaboration to advance knowledge of the cryosphere.

Isabella Velicogna (JPL and UCI) discussed GRACE measurements of time variable gravity, which provide a unique method for determining contributions to sea level rise from the polar ice sheets. She presented updated results for the ice sheet mass balances of Greenland (-240 ± -33 Gt/yr; Figure 6) and Antarctica (-154 ± -77 Gt/yr) over the last 9 years, using GRACE. She discussed comparisons of GRACE results with other methods, such as the mass flux method, and showed how they fit within the longer-term trends. She also assessed current uncertainties on ice sheet contributions to sea level rise. Comparing GRACE ice mass estimates with mass fluxes and radar altimetry data, she discussed improved constraints on Glacial Isostatic Adjustment (or GIA; the movement of the solid earth associated with ice mass loss) corrections. She also showed that regional scale measurements reflect an increase of mass loss in northwest Greenland. In Pine Island Bay, Antarctica, the mass loss is ongoing, despite a reduction in acceleration of the glacier after 2009. A clear link between regional ice loss and increased regional heat content in the oceans was demonstrated, using averaged Reynolds Sea Surface Temperatures (SST). She finally presented preliminary results for relative sea level changes, based on present-day mass losses from both ice sheets. The sea surface fingerprints due to both Antarctic and Greenland ice mass loss were shown, and how they represent the impact of both ice sheets on regional sea level rise around the globe.

Greenland Ice Mass Trend

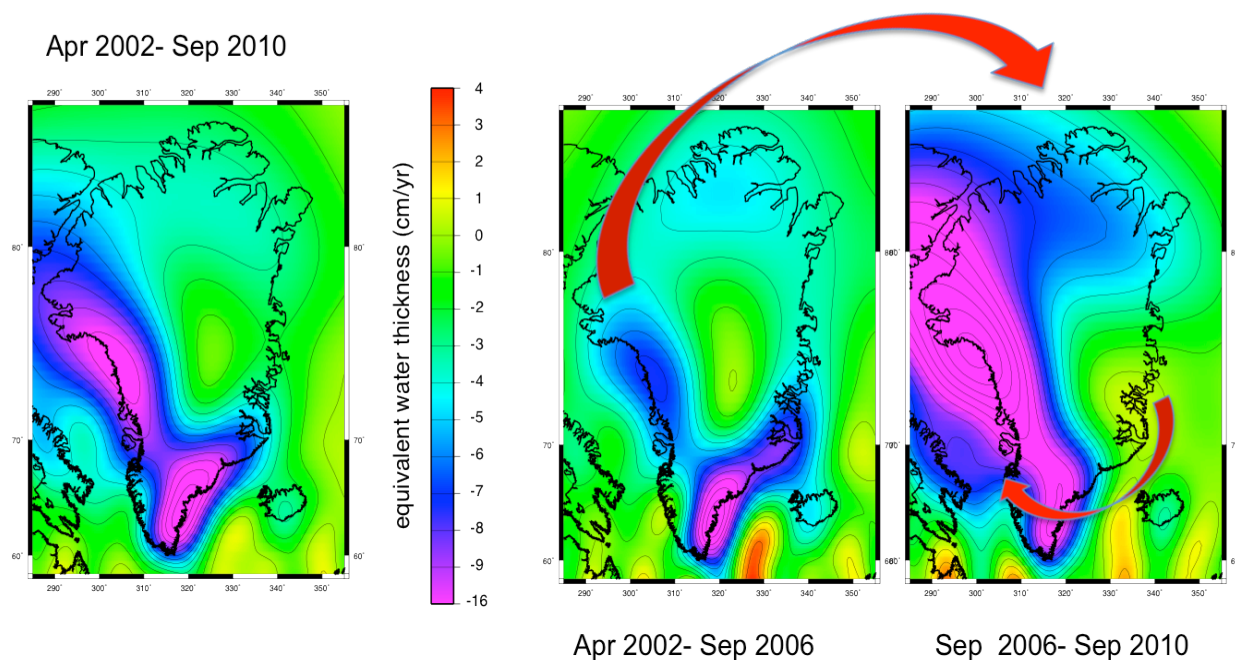


Figure 6: Greenland ice mass trend between April 2002 and September 2010, measured using GRACE data. Courtesy of Isabella Velicogna.

Dimitris Menemenlis (JPL and UCLA-JIFRESSE) discussed how ice mass loss from the polar ice sheets is governed by processes such as grounding line dynamics, ice-ocean interactions, possible enhancements from sub-glacial discharge, and ice dynamics effects, which are not well represented in the current generation of Earth System Models (i.e., models used for the IPCC Report). He explained that one of the major challenges in coupling an ocean model to a dynamic ice sheet is the disparity of temporal and spatial scales of climate processes associated with each component of the system. For example, ocean ventilation and ice sheet equilibration times of thousands of years, or the sub-kilometer spatial scales of oceanic vertical mixing or of ice sheet grounding line dynamics. He presented preliminary results from the recently initiated collaboration between JPL's Estimating the Circulation and Climate of the Ocean (ECCO) and JPL-UCI's Ice Sheet System Model (ISSM) projects, which bring together a cross-disciplinary team with expertise in eddy-permitting ocean, sea-ice and ice-sheet data assimilation. Generally speaking, ECCO is an ocean state estimation system that employs MITgcm, a global ocean circulation model developed by colleagues at the Massachusetts Institute of Technology (MIT), several of whom now work at JPL. Menemenlis presented, among other things, results on the sub-glacial water discharge from Greenland glaciers, and the way in which this can be modeled using the ECCO system (Figure 7). This is important in determining the amount of melting at calving fronts of land terminating glaciers, which control the retreat rate of such glaciers. He also mapped the link between warming SST along the Greenland

coast (as modeled by ECCO) and increased acceleration of corresponding grounded glaciers. Finally, he presented new capabilities implemented in ECCO to model melting rates under ice shelves. Melting rates are proving increasingly important in explaining sudden retreat of major glaciers, such as Pine Island Glacier. He also presented adjoint-data assimilation capabilities for this new melting-rate model, which can be used to understand the sensitivity of the ice-ocean system to melting and ocean circulation under ice shelves.

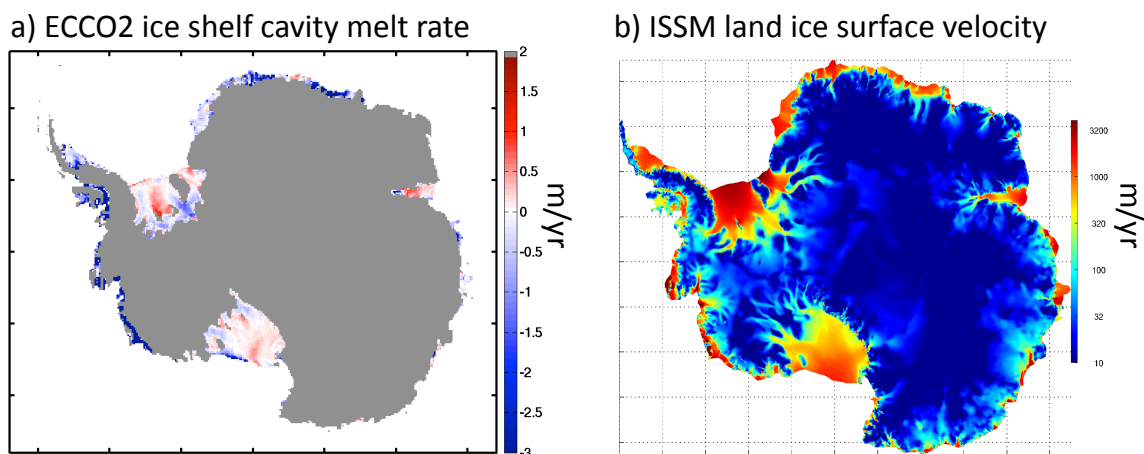


Figure 7: The interaction between ocean and ice sheets on rather small scales, e.g., in sub-ice shelf cavities around Antarctica and in narrow fjords around Greenland, may provide a key link between observed accelerated glacier flow and large scale oceanic variability and circulation changes. Critical processes on the oceanic side include topographic steering, eddy variability, tidal mixing and brine rejection by sea ice. For ice sheets (discussed by Eric Larour, below), critical processes include grounding line migration and higher-order stress coupling. Faithful representation of these ocean/ice-sheet interactions thus emerges as a new frontier for Earth System Models and it may well be the key ingredient in any coupled modeling effort that attempts to quantify and reduce uncertainties in sea level rise projections for the next century.

Eric Larour (JPL and UCI) discussed in detail issues pertaining to ice flow models used to represent the behavior of polar ice sheets and glaciers in the Earth System. In order to improve projections of future sea level rise in a changing climate, he showed the extreme need for better data to constrain ice sheet models, in particular, data regarding ice sheet geometry and bedrock position, which play a prominent role in the ice flow equations. He presented some of the ongoing efforts being conducted by members of the JPL and UCI ISSM teams in order to address modeling issues directly arising from such poorly constrained geometries, which have a direct impact on sea level projection. For example, the team is working to improve the integration of multiple heterogeneous datasets (spanning different regions and time periods) into the data assimilation process. Improved data assimilation will further improve the spin-up of transient (time varying) ice flow models, and simulation comparison to observations, including past rates of grounding line retreat and InSAR-derived surface velocities (Figure 1). Larour

also showed the strong dependence of grounding line dynamics on the bed roughness (at spatial scales of 10-50 m to over 1 km), which is on par with the influence of melting-rates under ice shelves. This supports a need for increased collaborations between ice flow modelers and ocean circulation modelers, such as those between the ECCO and ISSM teams.

Issues regarding the role of the cryosphere in sea level rise were then discussed in an extended open forum led by keynote speaker Rignot and session speakers Velicogna, Larour and Menemenlis, with some notable input from Michael Schodlok (UCLA-JIFRESSE). Coupling between the cryosphere and the different components of the Earth System was a pervasive theme, with emphasis on making the need for observations to constrain ice flow models a main priority, especially observations of ice thickness, surface ice flow velocity, thinning rates and bathymetry. It was also agreed that achieving good predictions is a long-term goal, and that for now, we should strive to reduce uncertainties. For example, can outside boundaries be provided of what the ice sheets might do over the next century? It was concluded that to determine such boundaries, the true goal is more realistic simulation of the rate at which melting occurs, which is hard to model. Grounding line migration, including its relationship to melt, is another critical issue, especially in controlling the evolution of ice shelves/ice sheets. Some of the panelists indicated paleoclimate studies may teach us about tipping points in the ice sheet/ice shelf system, though more data is still needed to reach robust conclusions.

Given the difficulty in tackling long-term projections, the feeling of the panel was that short-term (15-20 year) projections should be the focus, and one of the determining factors for making such predictions would be the knowledge of current temperature profiles in fjords around Greenland and near calving fronts of major ice streams in Antarctica. Another critical observation would be the bathymetry/cavity shape beneath ice shelves, which is not yet adequately covered in airborne surveys of Antarctica and Greenland (Operation IceBridge). Ice shelf behavior in ice flow models is very sensitive to the shape of the cavity under the ice shelf. One of the products of predictive modeling could be stochastic analyses, with ranges of probabilities (analogous to weather predictions) for successive levels of sea level rise. This would have the advantage of informing public policy more efficiently.

JPL is particularly well-suited to assist these efforts by (1) fulfilling the need for more time and funding for model development and data acquisition; (2) employing involvement of oceanographers in studying ocean-ice interactions; (3) enhancing observations, e.g. via upcoming missions, including IceSAT-2, follow-on GRACE, ice sheet motion (the Deformation, Ecosystem Structure and Dynamics of Ice, or DESdynl mission), and supporting *in situ* measurements of temperature and salinity under the ice shelves; 4) advancing data assimilation methods.

D. Session 4: Sea Level, the Solid Earth & Geodesy

Session 4 focused on the roles of the solid Earth and geodesy (related to frame of reference) in sea level estimation. Earlier in the workshop, in preparation for this session, keynote speaker, Mark Tamisiea, discussed the theory and measurements of the solid Earth and its gravity field that are essential for understanding sea level variability, providing some necessary background summarized below. This is followed by summaries of the session talks by Erik Ivins, Bruce Haines and Xiaoping Wu, and by Jean Dickey, all from JPL, as well as some key points from the subsequent panel discussion.

Background on Solid Earth Effects on Sea Level:

Tamisiea discussed the profound differences in material behavior of Earth's solid mantle and layered core on different time scales. On short time scales, the Earth behaves elastically, much like a spring would behave in accordance with Hooke's law. Transition to creeping (a more fluid deformation) behavior occurs at timescales of on the order of 20 to 200 hundred years, depending upon the depth, temperature and chemistry of the rock involved. This means a solid part of the mantle that is subjected to a constant surface stress over times much longer than this transition time scale (say tens of thousands of years), will deform at rates that are substantially larger than their elastic (short term) counterparts. At the time scales of the Last Glacial Age (LGA), the solid earth behaves as a very viscous fluid. On the time scales of terrestrial planetary lifetimes (~ 4.6 billion years, or since the Archean Expansion (AE)), the Earth behaves as an inviscid liquid and, hence, its ellipsoidal shape can be predicted from the same formalism used for rotating giant gaseous planets.

There is a special feature associated with slow viscous flows that affects how we measure sea level. The flow is in a state where the material may be considered to have 'memory', much like cold honey has when subjected to changing forces on the time scales of minutes. The mantle memory has a profound influence on sea level change. This is indicated from measurements taken along coastlines in Scandinavia and North America, where roughly 20 thousand years ago ice sheets existed. This is because the mantle *slowly* moves back to its position of gravitational equilibrium. As it moves, it exponentially relaxes the stresses associated with this flow, and eventually returns to a state of hydrostatic (or convective) equilibrium. This is important to the measurement of sea level, since the amplitudes, spatial scales, and global nature of the phenomenon tend to match up with those of ongoing sea level changes that are driven by present-day climate variability. A classic example of how the motions of the solid earth and 20th Century sea level rise intermingle in observational data comes from time series of tide-gauge measurements along the northern coasts of Germany and Poland, Arctic Russia and the western shores of the Baltic States. Here, the effects may be of the same order (about 1 mm/yr) and either of opposite sign (solid earth going up and shorelines emerging) or of the same sign (solid earth going down, shorelines submerging).

Considerable ambiguity comes from the fact that errors in a rebound model of the viscous Earth cannot be so easily separated from other long wavelength geophysical effects, biases and errors. Some of the longest tide gauge records (150-200 years) come from northern Germany. These are influences of the solid earth in what is called the 'near-to-intermediate' field of post-glacial rebound.

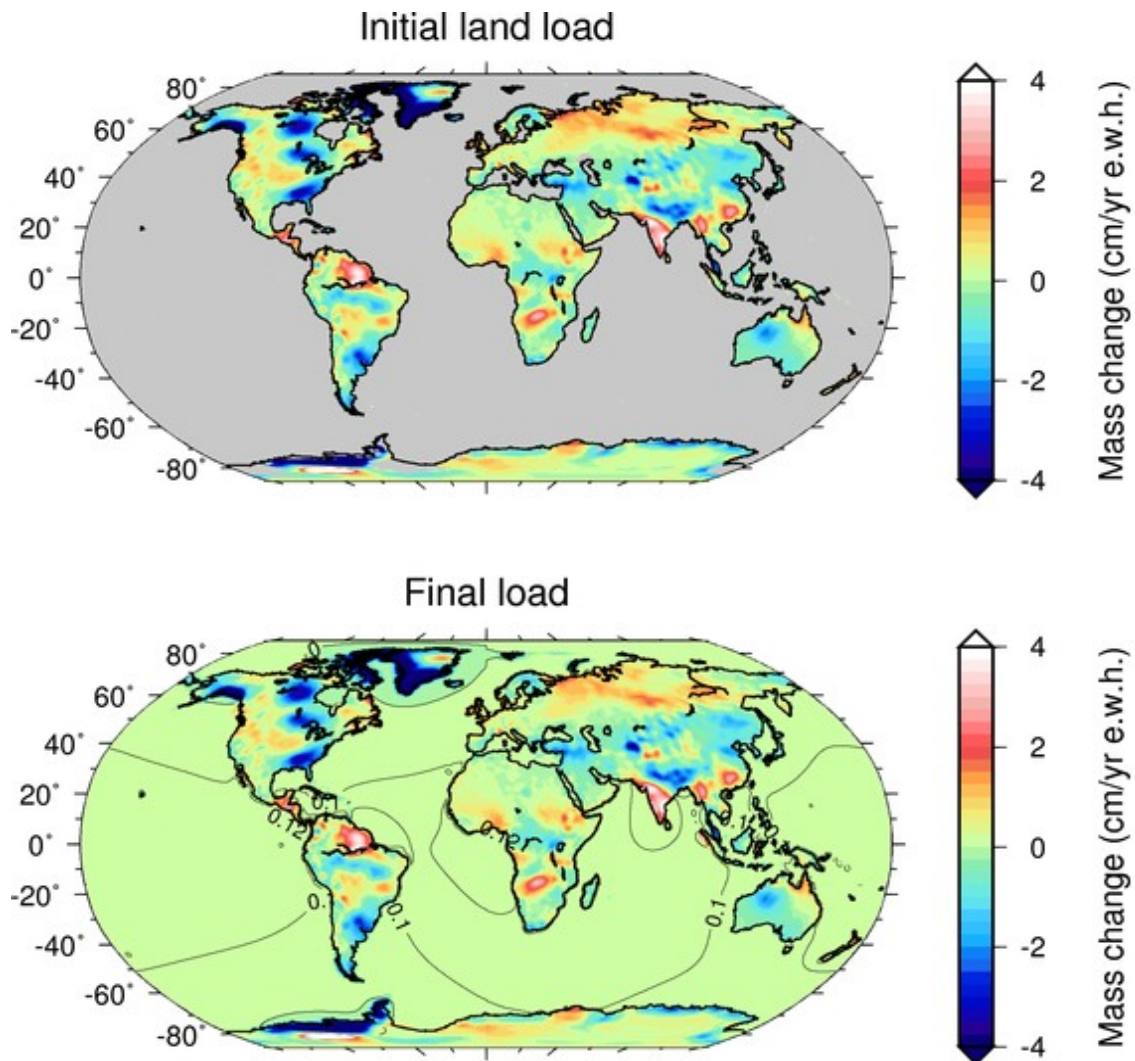


Figure 8: The top frame shows GRACE-determined mass trend in water height equivalent on the continents (Delft DMT-1, 2003-2009). Here, the oceans are masked out. The lower frame shows the global impact of the gravitational-elastic earth deformation coupling on the trend, which occurs both on land and in the ocean. Note the 12% higher rate of change in load in the Americas and Indian Ocean. If mass loss from the continents were to accelerate, the globally non-uniform water heights also accelerate. These computations are based upon observed continental mass changes recorded by GRACE mission data. Gravitation-deformation effects sum to form a higher rate of sea-level change along the eastern coast of the US. From Riva et al. 2010.

Far away from the centers of the former ice sheets (San Francisco, Honolulu, Tokyo,

Singapore, Christchurch, etc.) tide gauges are also affected by post-glacial rebound, but the amplitudes are smaller and of much longer wavelength. Ongoing changes of the shape of the Earth continue at present-day, largely influenced by the relatively slower moving deep mantle (GIA). This changes Earth's geoid, the geopotential surface corresponding to Earth's mean sea level if the ocean and atmosphere were in equilibrium. When the geoid changes, sea level follows. The fact that these effects must be accounted for in interpreting tide gauge data has been known for a long time. The canonical mean value for global corrections is about 1.2 mm/yr.

GIA corrections are also important to altimetry time series and to direct water mass change detection using space gravimetry (e.g., GRACE), although they are done in slightly different ways. For altimetry, both the geoid and total volume holding capacity (the ocean basins change shape) are important, while for GRACE the mantle mass changes need to be properly mapped to the area of the Earth's surface that is covered by oceans.

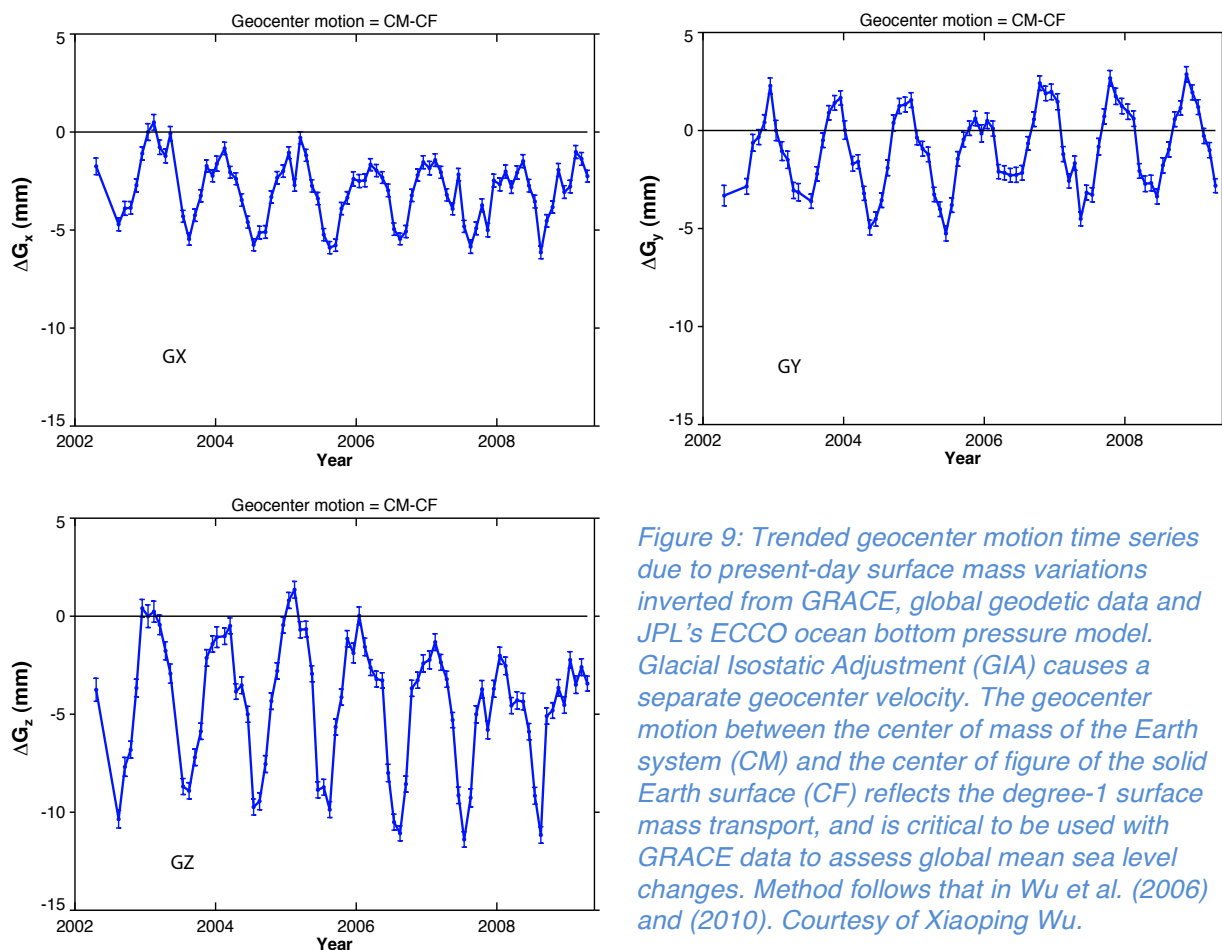
Lastly, the self-gravitational effects on sea-level that arise from continental ice sheet loss are important. Profoundly different sea level changes are predicted when the amount and geographical distribution of ice loss from the Greenland and west Antarctic ice sheets are considered, as opposed to when a uniformly inundated ocean is used. These differences will be projected into the future. For example, a 5.4×10^5 Gt loss (equivalent to 1.5 meters of rise) from the two ice sheets (in equal parts) is predicted to cause about 1.85 meters of sea level rise in San Francisco and Tokyo, but 40% smaller values at other coastal positions on the globe, such as Athens or Karachi.

Presentation Summaries:

In session 4, Erik Ivins (JPL) discussed in further detail the role of the deforming Earth in sea level estimation. He addressed global consequences of earthquakes, which can very rapidly change the shape of the Earth's crust, influencing ocean load distributions in ways that lack spatio-temporal coherence. Glacial isostatic phenomena also have global consequences, but are spatially and temporally coherent. He highlighted, as an outstanding research problem, determination of accurate GIA 'corrections' for both sea-level and Antarctic/Greenland ice sheet loss interpretations from GRACE. Additionally, he pointed out that tide gauges and Global Positioning Systems (GPS) are crust-fixed, whereas the geoid is center-of-mass fixed, so researchers must consider the implications for reference frame stability. Reference point considerations were an ongoing theme throughout the session.

Bruce Haines and Xiaoping ('Frank') Wu (both of JPL) gave related presentations. Wu discussed the effect of the center-of-mass (CM) center-of-figure (CF) motions that are induced by the spherical harmonic degree-1 part of the mantle-core return flow to the northern hemisphere (e.g., Figure 9). If the CM-CF offset rate is not accounted for in sea-level data analysis, it can result in an error of on the order of 1 mm/yr for estimates

of sea level rise. This topic lead into Haines' discussion of the importance of global geodetic reference frames, their stability, accuracy and secular (or non-secular) motion. A main point is that the primary measuring systems are embedded into the crust of the solid earth. The systems determine terrestrial reference frames by relative range to different external signals (very long baseline interferometry, or VLBI), or actively range (laser) to passive reflective satellites (LAGEOS-class space gravimetry) and actively ranging global navigation satellite system (GNSS). These three systems measure different quantities from which the reference frame of global geodesy is derived. Only if these systems continue to work together in the high quality and continuous mode that they currently are in, can we expect to use altimetry and space gravimetry with the level of measurement confidence to which we are currently accustomed.



A related poster presentation by Wu, Ivins and Donald Argus (also of JPL) showed that the effect of vertical motions of mass in Antarctica and Greenland may strongly mask the correct interpretations of GRACE for ice mass loss/gain trends, thus effecting our

estimates of sea-level change to the level of 0.2 - 0.5 mm/yr. Regional GNSS-determined vertical motions are critical to removing the mask correctly. Vertical motions of the solid Earth determined by GNSS ranging data have helped define the region of anomalous subsidence, and hence anomalous tide gauge time series in the Gulf of Mexico near the Mississippi Delta.

Jean Dickey (JPL) spoke on a peripheral topic to solid Earth, pertaining to the role of geodesy in satellite altimetry measurements of sea level. In an effort to provide some necessary background for researchers who are not familiar with the role of geodesy in altimetry, she showed a set of time series and trend comparisons that illustrated how frame of reference and other processing details can effect sea level measurements.

The expert panel for this session included keynote speaker Tamisiea and session speakers Ivins, Wu, Haines and Dickey. One additional topic of importance taken up by the panel involved the effects of Earth's rotation (polar wander) on the interpretation of global gravity, ocean altimetry and tide gauges. Mark Tamisiea stated that these effects are smaller than has been published in much of the literature over that past 15 years, suggesting a 0.2 – 0.25 mm/yr correction due to this particular GIA phenomenon. We can anticipate continued debate on this topic.

E. Session 5: Regional Sea Level Change

Session 5 linked several different topics related to regional sea level change. This session began with a fourth keynote-style presentation by Dan Cayan (Scripps Institute of Oceanography and United States Geological Survey (USGS)), who gave a comprehensive summary of the current state of regional sea level change research and its importance. This was followed by 2 speakers from JPL: Marc Simard, who is conducting a near global survey of the effects of regional sea level on coastal ecosystems, using mangrove trees as bio-indicators; and Alexander Rumaikin, who presented preliminary work conducted with Larry Breaker (Moss Landing Marine Laboratories) for development of an empirical prediction method for regional sea level change.

Regional sea level changes are subject to a set of global and regional processes that are imperfectly accounted for by regional sea level models. This uncertainty makes regional model simulations only marginally useful for planning purposes, but as sea level rise advances, such model estimates are clearly needed and continued model development should pay off in the future. In the meantime, probabilistic analyses (e.g., Perrette et al., 2011) that can be understood better by the public and attempt to separate the natural and anthropogenic components of regional sea level change can be used to set management priorities and better inform decision makers. To improve the applicability of models and new advances in understanding, the public needs to be

educated on the impact of sea level rise, particularly in regions that will be most affected. California, for example, is vulnerable to sea level rise along the open coast and within the San Francisco Bay/Sacramento and San Joaquin Delta. In order to identify vulnerable regions and provide accurate assessments of impact, it is necessary to have observing systems that provide adequate information for these regions.

a)

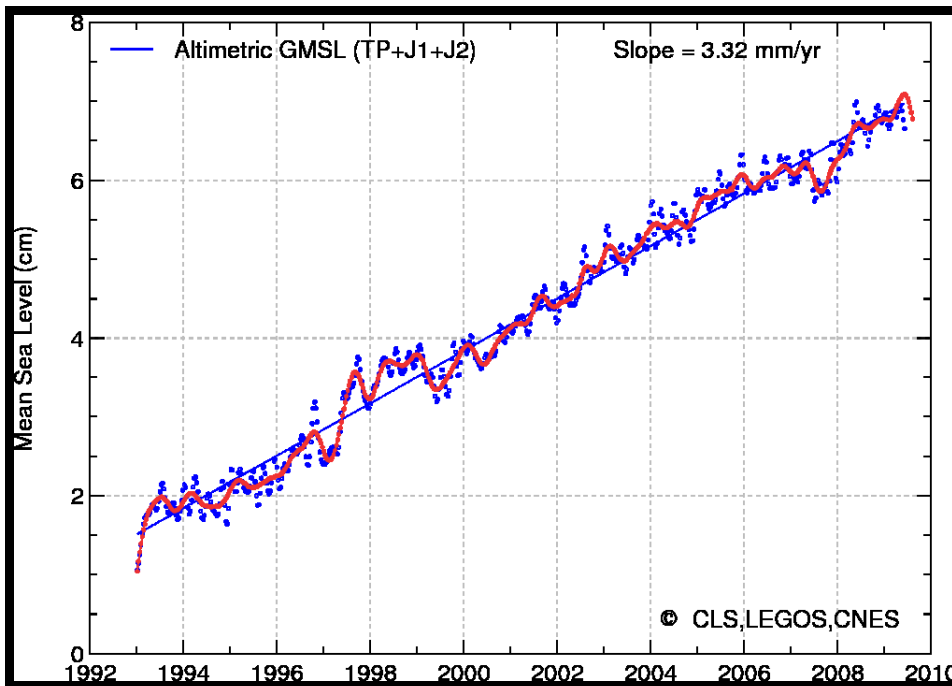
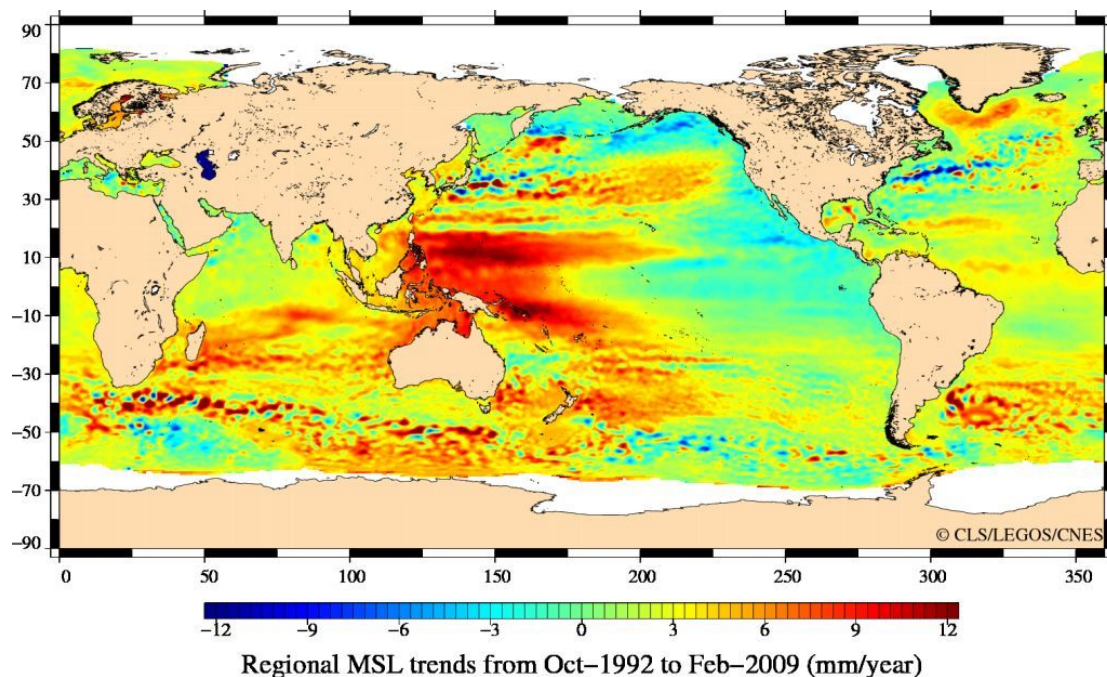


Figure 10: While measurements of sea level show an overall sea level rise (a), it is not evenly distributed (b). The impact of sea level rise on coastal regions will vary regionally.

b)



Dan Cayan began his keynote talk by pointing out that The Pacific Institute estimates that 480,000 people, a wide range of critical infrastructure, vast areas of wetlands and other natural ecosystems, and nearly \$100 billion in property damage along the California coast are at increased risk from flooding due to a potential 1.4 m sea level rise, if no actions are taken (Pacific Institute 2009). Over much of the 20th Century, sea level rise along the California coast has closely mirrored global sea level rise, but in recent decades sea level changes along there has leveled off or even slightly reversed, while global rates have increased. The hiatus period in US West coast sea level rise is expected to subside, and begin to increase at a rate significantly higher than global mean during the coming decade (Bromirski et al., 2011). Locally and regionally, in addition to long-period secular changes in sea level, storm-driven fluctuations, high tides and waves, as well as El Nino-Southern Oscillation (ENSO) effects, can combine to produce the most significant impacts. Thus, the coincident occurrence of storms and high tides should also be considered when mitigating the impact of regional sea level change on coastal areas.

Marc Simard spoke in more detail about how sea level change also threatens coastal habitats that are critical for survival of the ocean's food chain, as well as impoverished coastal populations along tropical coasts. In particular, mangrove forests, which host hundreds of species, are vulnerable to sea level change, as well as other forms of anthropogenic activity. Over 35% of mangrove forests have disappeared due to urbanization and the remaining forests, which are vital to fisheries, are threatened by long-term sea level rise (Valiela et al., 2001). Although they cover less than 1% of land, mangrove forests contribute significantly to the global carbon cycle through a direct and dynamic exchange of carbon with coastal waters. Peat depth in these areas is 1-2 m and in some places reaches 10 m. Thus, the impact of removal or die-off of mangrove trees on climate should not only account for its wood and root productivity, but also to its capacity to retain peat.

Alexander Ruzmaikin then gave an overview of how adaptive, long-term data record analysis tools can be used to de-couple the drivers of regional sea level change. De-coupling of linear and non-linear variations facilitate identification of natural climate variability modes, and help improve predictions. He and his collaborator, Larry Breaker, gave a detailed example of such a decomposition using a 150+ year tide gauge record from the San Francisco Bay. Such analyses applied to relatively long *in situ* and paleoclimate records could be used to complement shorter, but more geographically comprehensive satellite-based measurements of sea level and model simulations.

The discussion panel for this session included all 3 session speakers, Cayan, Simard and Ruzmaikin, as well as Dimitris Menemenlis (JPL and UCLA-JIFRESSE) to provide a coupled modeler's perspective. It was agreed that in order to better understand and project regional sea level changes, it is important to quantify the individual roles and coupling of regional processes, such as winds/storms, air-sea fluxes, geomorphology, coastal subsidence and erosion. These factors can then be combined with global sea

level models. Thus, multidisciplinary programs focusing on observation of high-risk regions are needed, in particular, in developing countries where observing systems are not in place.

The discussion also addressed the fact that in an effort to maintain simplicity, public discussions of sea level often neglect the extent to which the amount of sea level change and associated impacts are expected to vary regionally. Regional differences depend on the local coastal geomorphology, ocean currents, regional climate and weather, as well as global and regional geoid responses (discussed previously in section II D). To understand the impact of sea level change on coastal habitats and populations, it is imperative to understand the local and regional drivers of change. Improving our understanding of regional fluctuations entails improved regional climate modeling of historical and future periods, in order to elucidate the role of storms, habitats' role in preventing coastal erosion and long-term geomorphologic processes, such as subsidence and GIA.

Furthermore, the complexity and potential socio-ecological ramifications of regional sea level change need to be better communicated to the general public and to policy makers, since the need for immediate action on the policy/public infrastructure front may come before very accurate predictions of regional and global sea level changes are readily available. Proper communication of regional risks and their uncertainties by the science community would ideally motivate willingness by policy makers to develop appropriate policy actions, and motivate researchers to focus on regional, in addition to global, scale.

F. Session 6: JPL and The Way Forward

The final session of SLW-2011 began with a short talk by Steven Nerem (Cooperative Institute for Research in Environmental Sciences (CIRES) in Boulder, CO), which provided an external perspective on "The Way Forward" for JPL in the sea level research community. This was followed by an open discussion forum, headed by Eric Lindstrom, Tony Freedman (JPL Program Manager for Earth Science Research and Advanced Concepts), Lee-Lueng Fu (JPL Project Scientist for Jason 1 and 2), Steven Nerem and Graeme Stevens (Director of the JPL Center for Climate Science, the sponsor organization for the present workshop, SLW-2011), with significant input from keynote speaker John Church, JPL Ocean Group Supervisor Tong Lee, and several others.

Throughout the session and in subsequent discussions during the weeks following SLW-2011, 3 primary outcomes were achieved:

- (1) A concise list of **major science priorities** that JPL is particularly well-suited to address in the near future were identified
- (2) A **conceptual map was developed to illustrate how different satellite and airborne missions, climate modeling efforts and data analysis projects taking place across NASA-JPL relate to one another in the context of sea level research**, and how these components can work in sync to streamline progress toward improved sea level estimation and projection
- (3) **New internal and inter-institutional collaborative efforts** involving JPL researchers in different disciplines were conceived

The science priorities identified in (1) are as follows:

- **Support continuity of satellite measurements** like Jason & GRACE (this is important for Science, as well as provides an early warning system for climate change)
- **Support development of new missions and exploit existing ones** for data on...
 - topography under the ice sheets/shelves, ice velocity, elevation, mass, deformation & terrestrial parameters (e.g., IceSat-2; GRACE II; DESDynI; GRASP and OASIS, described in section III(A) below)
 - interannual variability in the water cycle (e.g., Surface Water Ocean Topography (SWOT), Soil Moisture Active Passive (SMAP), Aquarius and CloudSat Missions)
- **Continue development of Ice Sheet System Model (ISSM)**, especially ocean-ice sheet/ice shelf interaction (coupling with ECCO), data assimilation, development of adjoint capability, etc.
- **Develop model downscaling infrastructure for regional sea level study** using high-resolution regional data assimilation embedded in global data-model synthesis (i.e., ECCO), with the goal to improve regional sea level projections (discussed below)
- **Develop multi-decadal and coupled model reanalysis using satellite observations and JPL data-model synthesis systems** (ECCO series; ISSM; regional downscaling infrastructure)
 - This is important to understand natural vs. anthropogenic climate contributions, needed for refinement of model physics & improved climate projections
- **Host online Sea Level chat room on JPL intranet** (managed by PO.DAAC) to foster interdisciplinary collaboration and trouble-shooting for sea level issues

(under development)

Outcome (2) is illustrated by Figure 11, which shows how various aspects of JPL and NASA efforts relate to one another in the context of sea level research.

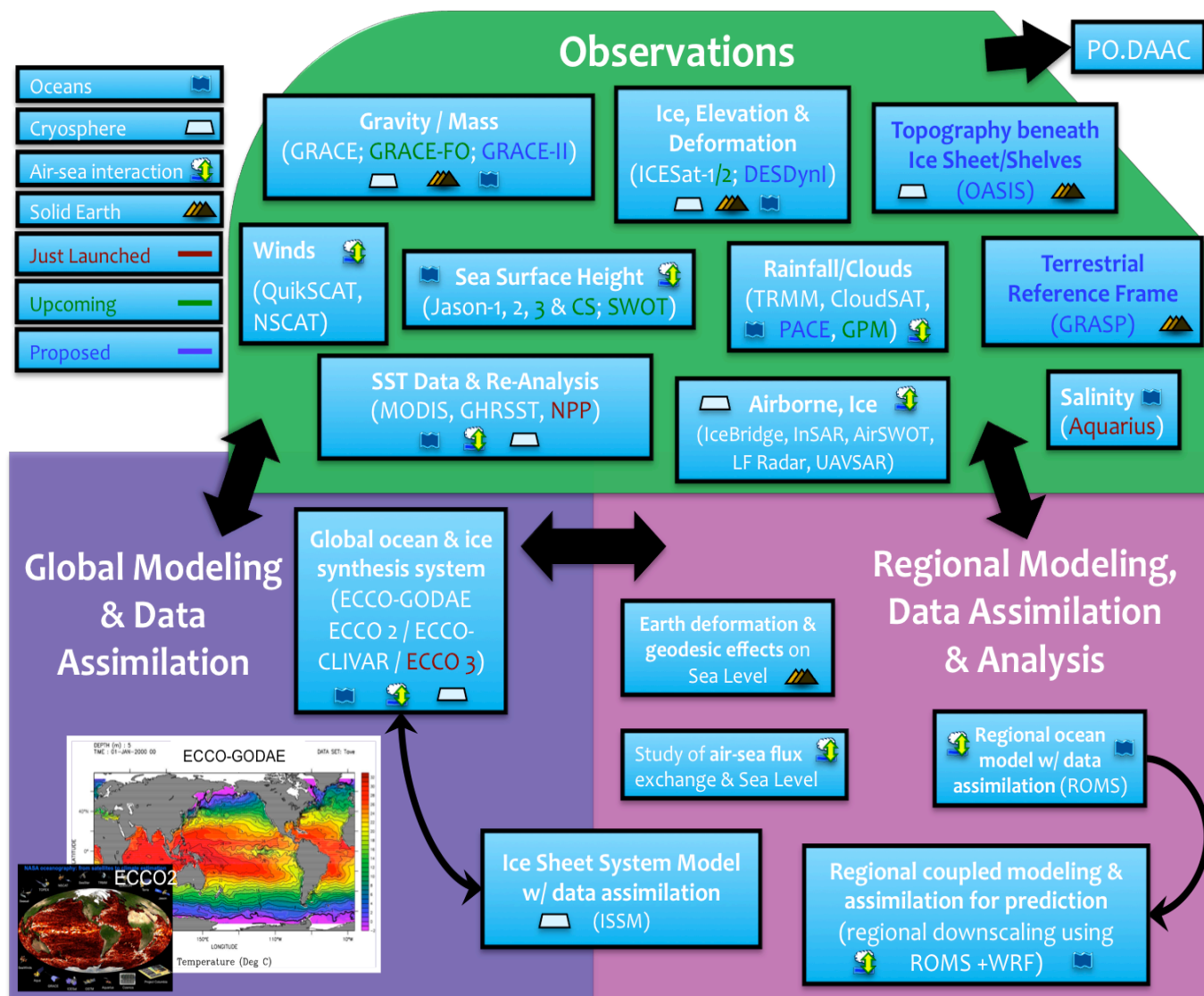


Figure 11: Relationships between NASA/JPL missions and sea level research at JPL across different disciplines.

Examples of ongoing and upcoming efforts related to SLW-2011 (Outcome 3) are described in section III, subsections A through D.

IV. Enhancement of Sea Level Research and Collaborations at JPL

A. Importance of NASA-JPL Satellite Missions in Understanding Sea Level Rise

For decades NASA satellites have been important assets in monitoring changes in the climate system. Radar altimetry from TOPEX/Poseidon and Jason satellites have provided nearly two decades of global sea level observations. The analysis of these measurements significantly enhanced our understanding of the global oceans. They not only confirmed what tide gauges already indicated: that sea level is rising at a rate that will threaten coastal communities and ecosystems, they also showed that rates over the last two decades are significantly higher than those of the previous 100 years—implying an acceleration of sea level rise during the 20th Century.

Since the early 2000s, GRACE satellites have provided measurements of the Earth's gravity field. From these, changes in the distribution of mass across the globe are inferred. GRACE helps researchers separate the contributions to sea level rise caused by loss of mass from ice sheets, ice caps and glaciers, from sea level rise caused by thermal expansion of the warming oceans. Complemented by Argo, a global array of floats that help measure the density-related component, these observing systems can account for the causes of global sea level rise for the period from 2005 to 2011 (Leuliette and Willis 2011).

Besides the ocean, other components of the water cycle also require continuous monitoring to improve our understanding of current and future sea level change. In a warming climate, accurate knowledge about evolution of the ice sheets in Greenland and Antarctica is crucial for predicting rates of future sea level rise (Church and White 2011). Terrestrial water storage is an indicator of residence time of water on land. Observations provide information on how long water is stored on the continents, until it runs off into the ocean and contributes to sea level change. GRACE observations yield estimates of ice sheet mass loss (Velicogna 2009), and changes in terrestrial water storage (Swenson, Yeh et al. 2006; Syed, Famiglietti et al. 2008) that form the foundation for model constraints and future predictions.

Present day satellite observations give us a more complete picture of the Earth and its climate than ever before. These data have enabled study of the physical processes that drive climate change on interannual to decadal scales from a global perspective. Observations from sea level related missions have led to a substantial improvement in our knowledge of sea level changes and their causes on these time scales. However, ***continuation of these missions is crucial***. Gaps in data could miss critical events, such as a temporary acceleration in ice loss or a transfer of water from ocean to land.

Such events can provide insight into critical drivers of climate change. Missing them could jeopardize our ability to predict future changes.

Sustaining present day observations serves an additional purpose, highly relevant for understanding future sea level rise. Paleoclimate records of sea level rise suggest that rates of 3 to 4 times the present are possible in a warming world. Without satellite altimetry and gravimetry, however, the ice sheet changes that would cause this, and the resulting acceleration in global sea level rise, might take decades to detect. With these observing systems, such acceleration would be detectable in a matter years rather than decades. In this way, satellite altimetry and gravimetry provide an “early warning system” for global climate change.

Future missions are planned or proposed to support advances in sea level science. In the near future, Jason 3 and GRACE FO will be launched to continue the altimetry and gravimetry data sets. GRACE II, part of the decadal survey, will be launched in 2020. The SWOT mission, also to be launched in 2020, will provide information on water reservoirs. Ice sheet properties and evolution are monitored by IceSat and will be continued by the upcoming IceSat-II mission. The IceBridge project – an airborne field program designed to close the gap between IceSat and IceSat II – is taking measurements of the bathymetry under the ice shelves, a crucial component for modeling ocean-ice sheet interactions, in addition to several other parameters relevant to the surface mass balance of the ice sheets. Another important factor in accurately determining sea level trends is sufficient knowledge of the terrestrial reference frame (TRF). The GRASP mission will provide accurate measurements of the latter, with the goal of eliminating spurious trends in the sea level record due to uncertainties in estimates of the TRF.

Finally, the Orbiting Arid Subsurface and Ice Sheet Sounder (OASIS) satellite is a *proposed* JPL mission (under review by NASA’s Earth Venture Program) with the potential to revolutionize ice sheet model development by providing detailed information about the topography under the ice sheets, and with the potential for providing additional vertical profile information within the ice. OASIS will also provide data on terrestrial reservoirs that may help to better understand how terrestrial water storage relates to sea level. Furthermore, high-resolution measurements of the ocean surface dielectric, combined with satellite sea surface temperature (e.g. from the Moderate Resolution Imaging Spectroradiometer (MODIS) or the GHRSSST Optimum Interpolation with AVHRR data products) observations will allow for inference of sea surface salinity at unprecedented resolutions. This will compliment observations in progress by the Aquarius surface salinity mission, and may help in understanding the thermosteric contributions to sea level. During SLW-2011, it was widely agreed that in addition to continuation of current and upcoming missions, ***support for the proposed OASIS mission is critical.***

SLW-2011 has shown that JPL has a history of contributing to groundbreaking findings in sea level research through their major technological advances in satellite development. The workshop emphasized the importance of continuation and development of satellite missions that monitor different components of the sea level problem, as well as a requirement for coordination of lab-wide resources to tackle the interdisciplinary aspects of the issue of sea level rise.

B. Efforts to Enhance Understanding of Ice Sheets and Ice-Ocean Interactions

Several new and ongoing projects are taking place within JPL (and with external collaborators) involving the ECCO and ISSM projects (described in Section II(iii) above). These are part of a larger-scale effort to enhance understanding of the polar ice sheets and their role in sea level for eventual use in more accurate regional and global projections of sea level.

Since SLW-2011, the ISSM model code has been made publically available. A workshop conducted by the JPL-ISSM Team and geared toward potential users at other institutions worldwide took place in December 2011. On the development side, particular focus is being given to so-called ‘adjoint’ capabilities, which would be a significant advancement for ice sheet modeling. Meanwhile, regional scale coupling efforts between ISSM and ECCO, involving team members at JPL, UCI and MIT have continued development. Most recently, collaboration has been initiated between the members of the JPL ISSM team and colleagues at NASA Goddard Space Flight Center, who are involved in the development of the Goddard Earth Observing System Model, Version 5 (GEOS-5) atmospheric general circulation model (AGCM), with the goal of coupling ISSM and GEOS-5. Development of an ice sheet surface mass balance model to serve as a possible interface between GEOS-5 and ISSM is underway. In preparation for development and assessment of the coupled system, an intercomparison of different atmospheric and oceanic re-analysis products that affect surface mass balance, as well as those that affect melt rates under the ice shelves, and how different climate modes are represented in those products, has also been initiated. Aspects of these projects have been partially funded, but further funding is needed.

Long-term goals include (1) global scale coupling between ISSM, ECCO and an atmospheric model, most likely GEOS-5—although, depending on available funding, other candidates may be considered; (2) developing this coupled global system for use in studying long term global and regional sea level projection scenarios and sensitivities. To tie ISSM-ECCO to projections, we can, for example, force with the ice-ocean system with IPCC future atmospheric forcing scenarios, and examine sensitivities of projections to various internal and external ice-ocean model parameters. These results could then

be compared to results from the fully coupled ISSM-ECCO-GEOS-5 system. Success in these endeavors, however, requires many intermediate steps that have yet to be accomplished, despite the fact that ISSM and ECCO are both state of the art models, using state of the art data assimilation techniques. As discussed in Section II C, for these efforts to be successful, we must first and foremost expand and continue available observations to support these efforts, as well as offer funding specifically designated for software development for these models.

C. Downscaling Effort to Tackle Regional Sea Level Change

Two key uncertainties associated with sea level rise projection are (1) the effects of the Greenland and Antarctic ice sheets, and (2) regional sea level change (Nicolls and Cazenave 2009). Both of these aspects were discussed at SLW-2011. The former is just one of many factors that affect the latter. Regional sea level change is particularly important, because of the large population density along many coast-lines around the world. During the workshop, it was noted that satellite altimeter data shows a highly inhomogeneous spatial pattern of sea level trends, which includes effects of climate variability and change; in some regions, the sea level rise is a few times larger than the globally averaged sea level rise (e.g., Nicholls and Cazenave 2009; Figure 10). The resolutions of IPCC models are still too coarse to adequately resolve regional/coastal sea level changes for decision-making purposes. Therefore, a downscaling approach was suggested to couple coarser global ocean models with high-resolution regional/coastal models. The global models to be used in this scenario synthesize diverse observations from global ocean observing systems that are typically inadequate in covering the coastal region. The resultant global ocean data assimilation products provide optimal lateral boundary conditions to constrain the regional/coastal models. Such a downscaling approach maximizes the utility of open ocean observations and dynamics to provide regional sea level estimates through the regional models. The regional models can then be used to assimilate sparse observations in coastal regions to provide further constraint on coastal sea level estimates. Recognizing the role of the coupled regional climate systems on sea level, the regional ocean models should also be coupled to high-resolution atmospheric models (such as the Weather Research and Forecasting Model, or WRF) and land hydrology models.

Plans are in progress between 2 research groups within JPL working on model-data assimilation on different spatial scales: the ECCO group and a group working with a version of the Regional Ocean Model System (ROMS) coupled to WRF. JPL is in an excellent position to take on such a downscaling effort, in order to tackle the regional sea level issue, because of the following capabilities: (1) JPL already is at the forefront of global ocean data assimilation through the ECCO Consortium efforts, with advanced assimilation systems that synthesize most datasets from open ocean observing systems; ECCO products are also being updated on a routine basis. (2) JPL already has a high-resolution operational system for analysis and forecast of the regions off the

US west coast. (3) Through the UCLA-JPL Joint Institute For Regional Earth System Science and Engineering (JIFRESSE), JPL has established collaboration with UCLA on a regional coupled ocean–atmosphere (ROMS-WRF) model that assimilates both ocean and atmosphere data. These important capabilities can and should be combined to tackle the regional sea level problem (Figure 12).

Downscaling from a global ocean model to a regional model is not new. However, existing downscaling efforts focus on ‘nowcasts’ and forecasts on short time scales (days to weeks). There has not been any systematic effort to develop a regional ocean reanalysis system that can help study sea level variability and change in past decades. Such a reanalysis system is important to the attribution of regional sea level change in past decades and helps reduce the uncertainty of future regional sea level projection on timescales relevant to climate change.

ECCO global ocean-ice synthesis system

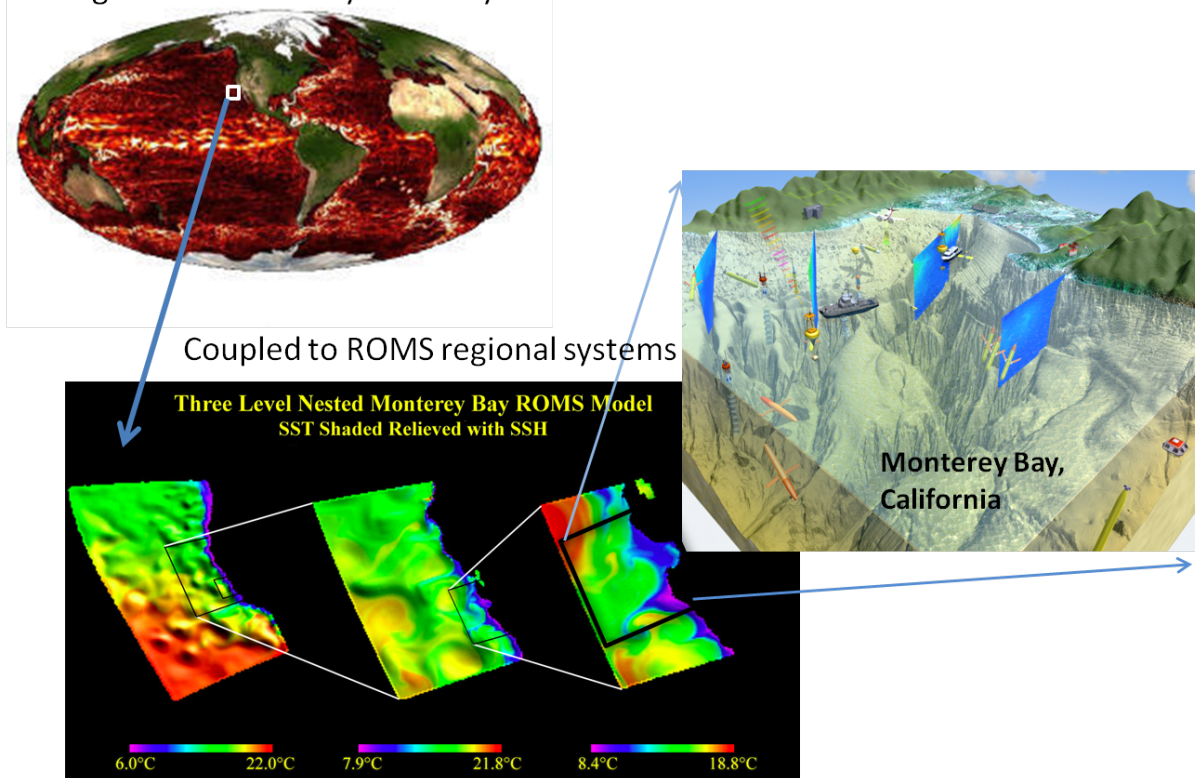


Figure 12: Downscaling global observations and dynamics to constrain regional sea level estimates is an important aspect of sea level research with strong societal relevance. JPL has advanced capability in estimating the state of the global ocean using global observations, such as the ECCO state estimation (<http://ecco.jpl.nasa.gov>). JPL has also developed the capability to downscale global dynamics to regional scales using the Regional Ocean Modeling System (ROMS, <http://ocean.jpl.nasa.gov>). However, the downscaling has not taken advantage of the ECCO state estimation. An envisioned effort for the future will bring these two capabilities together to allow global observations and dynamics to impact regional sea level research.

The US west coast is an ideal location to embark on the endeavor of developing a multi-decadal regional reanalysis system, because of a high-resolution coastal altimeter product for sea level and a scatterometer product for coastal wind that became available and housed by PO.DAAC recently. Moreover, there is a very unique, multi-decadal *in situ* dataset, from The California Cooperative Oceanic Fisheries Investigations (CalCOFI), off the California coast. These satellite and in-situ measurements provide strong observational resources upon which the regional reanalysis system can be built. The regional coupled system can then be made “re-locatable” to other regions of the world (e.g., regions with low-lying coasts) when observational resources for those regions become available.

D. Collaboration with the US Navy

There are potentially rich opportunities for collaboration between NASA/JPL (and the established partnership of scientific collaborators at various institutions), the US Navy, and/or the Department of Defense to deliver applied science data products for decision support. An NRC (2011) study was recently completed at the request of the Chief of Naval Operations to assess the national security implications of climate change on US naval forces (i.e., the US Navy, Marine Corps, and Coast Guard). With regards to future research priorities the NRC report highlighted that “U.S. naval forces will become even more dependent in the future on observations, analysis products, and forecasts of the global environment to carry out its mission”. Specific findings included the need to improve “coupled models and climate forecasting on seasonal-to-decadal timescales” and to give “special emphasis to regional aspects of sea-level rise, and sea-ice concentration and extent, because of their relevance to coastal infrastructure and operational needs” and increased Navy involvement in the “development of an Arctic Observing System, specifically with respect to development and deployment of in situ and remote sensing systems”.

Additionally, the Navy has established a Task Force on Climate Change (TFCC) which provides a cross-cutting assessment of climate change risks and research needs relevant to the Navy. The TFCC has identified two priorities for near-term (2011-2014) assessments: climate change impacts to naval operations in the Arctic and sea-level rise impacts to the US Navy’s coastal installations around the world. The Navy’s motivation for sustained attention to these topics is illustrated both in the NRC report and in the Department of the Navy memorandums, *Navy Climate Change Roadmap* (2010) and *Navy Arctic Roadmap* (2009).

The findings from the NRC report and priorities of the TFCC suggest the potential for increased coordination and collaboration between the respective research and applied science programs of the Navy (e.g., the Office of Naval Research or ONR), DoD (e.g., the Strategic Environmental Research & Development Program or SERDP), and NASA.

As a practical next step, a workshop could be organized between the NASA/JPL community and appropriate Navy organizations (engaged through the TFCC) to explore focused opportunities for increased collaboration in observations and modeling of Arctic systems and (in selected areas) local- to regional-scale sea level rise. An example of one outcome of such a workshop might be the identification of pilot projects that leverage and mutually benefit NASA ROSES, DoD SERDP, and Navy ONR resources in a coordinated fashion. In addition to satellites, there may also be opportunities to combine NASA and Navy resources for the near-term deployment of airborne and *in situ* observational assets.

A representative from the TFCC attended SLW-2011, and more recently, a visit was made by Rear Admiral David Titley, Director of TFCC, to JPL to discuss potential collaborations between the TFCC and researchers at JPL (<http://climatesciences.jpl.nasa.gov/seminar/2011-11-climate-navy>). Communication on this matter is ongoing.

V. Societal Need and Practicability

After advancing the technology required to measure global ocean surface topography (OST) from space and completing almost nineteen years of measurements, JPL is now helping to move sea level measurements into an operational mode. It has become increasingly relevant for the laboratory to focus attention on the science and societal benefits of the OST missions, particularly with respect to sea level rise.

While it was primarily a scientific event, SLW-2011 incorporated several non-research elements intended to address some of the social issues associated with sea level change. These activities included a lab-wide seminar and a student art exhibit. In addition, a related review of JPL's role in sea level rise research was conducted in advance of the workshop (see Section IV C below). These activities are summarized below.

A. Sea Level Seminar

In the week prior to SLW-2011, JPL's Center for Climate Sciences hosted a seminar on some of the regional (e.g., societal, ecological, infrastructural) implications of sea level rise. One purpose of the seminar was to provide a real-world context for participants in the science discussions that followed in the workshop.

The seminar speaker was Will Travis, executive director of the San Francisco Bay Conservation and Development Commission ([BCDC](http://www.bcdc.ca.gov/)¹). The commission was the nation's first state coastal management agency when it was created in 1965. Its primary objectives are to protect and enhance the San Francisco Bay and encourage its responsible use. In his talk, "An Integrated Regional Climate Strategy: An Impossible Dream?", Travis discussed the public policy implications of sea level rise in the San Francisco Bay region and the regional governmental response. He provided a socially-relevant perspective on why we at NASA and JPL should care about regional sea level rise, even though the bulk of the lab's research is based on global measurements.

The seminar emphasized the regional and policy implications of sea level rise on coastal areas, where a large subset of the global population resides. It was intended to encourage discussions in the workshop the following week about what could be done to help regional and local communities struggling to make responsible decisions in response to rising sea level. With its capabilities and expertise, JPL may be in a position to provide assistance to decision- and policymakers, and we can seek more opportunities to help meet the needs of civic leaders and society.

Approximately forty people attended the pre-workshop seminar, which was open to the JPL community. A video of the talk was also played during the lunch break on the second day of the workshop, giving people who were unable to attend the seminar a chance to view it. Travis is an engaging and highly knowledgeable speaker. The seminar is available online, along with the accompanying slides, on the JPL [CCS web site](http://climateciences.jpl.nasa.gov/eventsprograms/seminararchive/20110825regionalclimatestrategy/)².

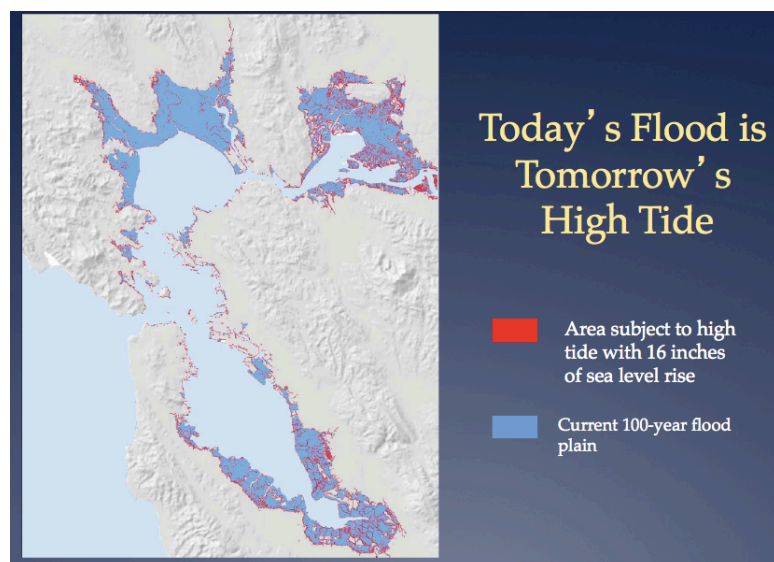


Figure 13: Land filled regions of the San Francisco Bay are increasingly subject to inundation from long term rise in sea level.

¹ <http://www.bcdc.ca.gov/>

² <http://climateciences.jpl.nasa.gov/eventsprograms/seminararchive/20110825regionalclimatestrategy/>

B. Student Art Exhibit

During both Will Travis' seminar and SLW-2011, an art exhibit on the theme of sea level rise was on display in the lobby of the building where the workshop took place. The art pieces were created by students at Pasadena's Art Center College of Design for program entitled 'Project Coastal Crisis', a collaboration between the Long Beach Aquarium of the Pacific and the *Desingmatters* program at the college.

For this project, students were "challenged to translate...scientific data on sea level rise and coastal resiliency into readily accessible public awareness communications and educational tools."³ They were asked to develop interactive and static exhibits suitable for a public setting that would promote public awareness of the impacts of sea level rise. The objective of the project was to merge science with art in a way that enhances public understanding of the science, impacts and risks of sea level rise.

Selected elements of three different student projects were displayed at JPL. These included:

- Our Rising Seas-- interactive elements designed to appeal to young children and promote dialogue within families
- Sustainable Aquaculture -- a pinball machine illustrating the benefits of integrated aquaculture strategies
- Think Sink -- products designed to lead people to a proposed educational website called www.thinksink.org



Figure 14: Elements from an Art Center College of Design student exhibit on impacts of sea level rise at JPL.

³ "Sustainable Design Strategies for Coastal Resiliency" brochure, The Aquarium of the Pacific Studio at Art Center College of Design.

C. SLR & Decision-makers

In early January, JPL's Center for Climate Science requested an examination of how JPL's capabilities and expertise could help meet the needs of society with respect to impacts from global and regional sea level rise. The questions to be addressed included: How can we 'operationalize' our data streams or synthesize them to make them more useful for stakeholder agencies or even commercial/industrial users? What funding opportunities might be available to continue our integrated research efforts and support decision-makers?

One objective of the review was to see to where the needs of public policymakers align with the goals of science/mission funding organizations and how research efforts could lead to societal benefits.

JPL is a leader in the direct measurement of sea level and has contributed abundant research on sea level variation and ocean circulation since the launch of Seasat in 1978. The lab has continued the ocean altimeter legacy with TOPEX/Poseidon (1992), Jason-1 (2001), and OSTM/Jason-2 (2008). The launch of Jason-3 in 2014 and future Jason-CS, and SWOT missions will provide continuing opportunities for the development of science and societal benefits.

What does JPL offer?

JPL has all of the critical components required to assess global sea level change: 1) observations, 2) advanced technologies, 3) theoretical understanding, 4) modeling and assimilation/data synthesis systems, and 5) historical datasets that allow for advanced ocean, cryosphere and atmospheric studies. These elements are all necessary in order to understand and investigate the multidisciplinary nature of sea level.

What do decision-makers need? Information not data!

Coastal community leaders at the local, state and national levels are involved in decadal and multi-decadal planning for changing sea level. They are currently using information from a variety of sources, such as the IPCC Fourth Assessment Report and NOAA. In order to make valid planning decisions, they require more specialized information:

- Accessible knowledge and information targeted to the specific needs and goals of their stakeholders (local and regional rather than global)

- Information from a broad range of scientific disciplines combined into a comprehensible message on coastal hazards of climate change
- Standard methods for assessing impacts and uncertainties (and education on the method)
- Clarity on probable vs. possible outcomes (in contrast to highly accurate measurements) on time scales of 50 to 100 years into the future.

Decision support can only be as good as the data used. On the other hand, no degree of accuracy in a current measurement of sea level will provide useful information for long-term outlooks for coastal planners. Information, not data, is what will be used.

The [NOAA interactive web page](#)⁴ is an example of information readily available on the coastal effects of sea level rise. This is a type of what may be considered ‘grey data,’ in that it does not actually reflect the local potential sea level rise, but rather, shows the local reflection of global sea level change. It does not provide an accurate assessment of the impacts of sea level change.

Gap analysis

Decisions are currently being made with incomplete information. JPL has the capability to customize integrated Earth system data and models on regional to local scales, which could allow for improved planning for coastal communities. Currently, research results and the information that decision-makers use are disconnected, resulting in a temporal and spatial information gap. While a significant effort will be required to fill this gap, ***JPL is in a position to lead such a task.***

JPL strategy

Through the Outcomes of SLW-2011, we are in a position to develop an assessment and projection capability for regional sea level rise using integrated models, data products (i.e., CCAR interactive/reconstruction) and possible pilot projects.

At the same time, we must engage stakeholders through community collaborations, as well as work with state and academic organizations. The goal would be to develop data products, information, and climate and/or sea level models with some predictive capabilities on regional scales.

Some research priorities that can lead us in the direction of an integrated approach to connecting JPL science and technology capabilities with stakeholder needs include:

⁴ <http://www.csc.noaa.gov/slr/viewer>

- Access to high quality measurements
- Appropriate tools (models, technology)
- Improved understanding of complex Earth system interactions
- Predicting local/regional sea level rise (downscaling global models)
- Identifying gaps in science, data, info
- Improved climate forecasting (climate models)
- Downscaling global data to regional (models)
- Quantifying uncertainties in context of risks and impacts on decision making
- Scenario analysis

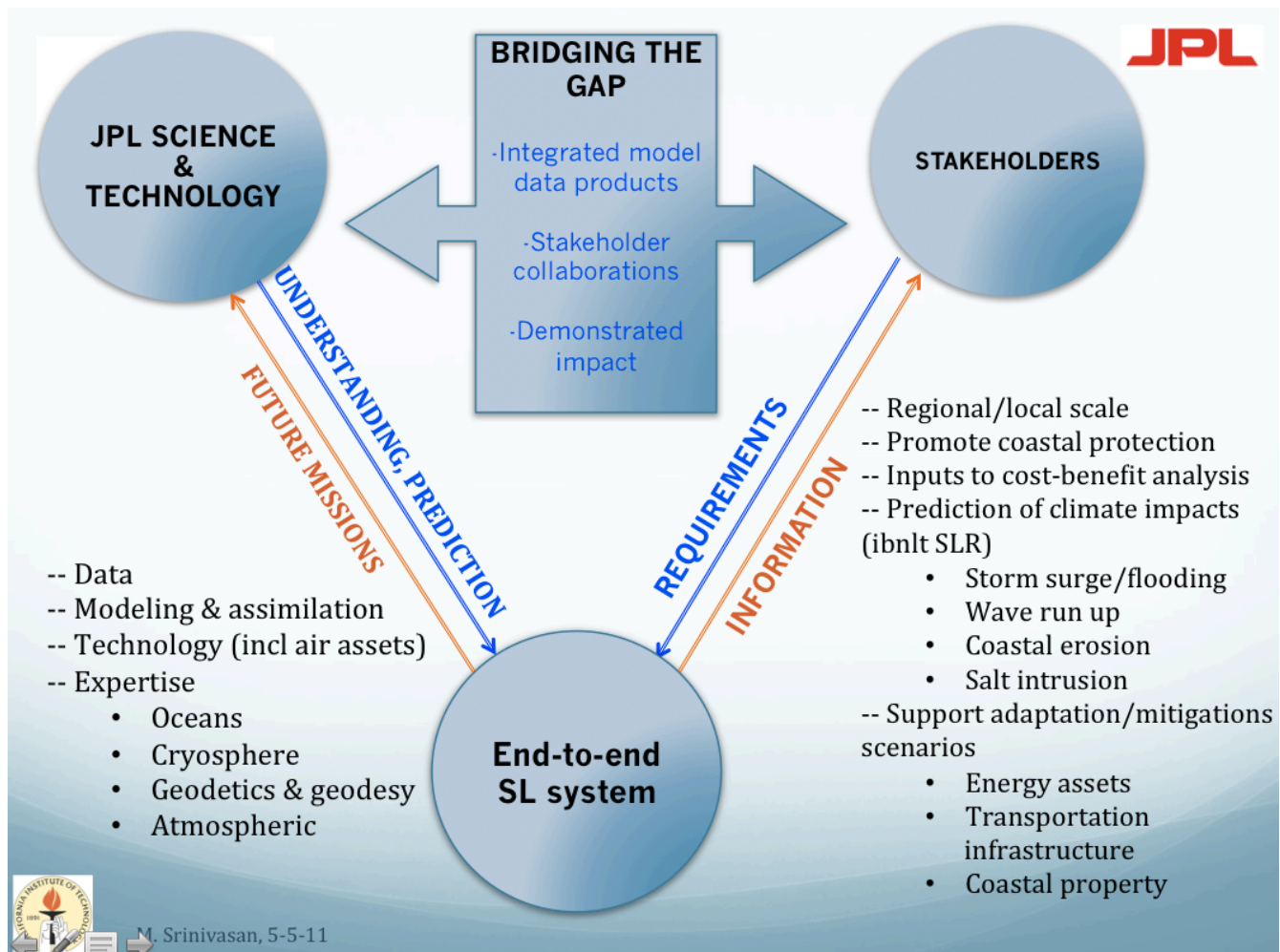


Figure 15: Links between JPL capabilities and stakeholder needs.

VI. References

- AGU Press Release, "After a three-decade hiatus sea level rise may return to the West Coast", http://www.agu.org/news/press/pr_archives/2011/2011-17.shtml
- Church, J. A. and N. J. White (2011). "Sea-Level Rise from the Late 19th to the Early 21st Century." *Surveys in Geophysics* 32(4-5): 585-602.
- Department of the Navy (2010), *Navy Climate Change Roadmap, Memorandum for Distribution* (May 2010)
- Department of the Navy (2009), *Navy Arctic Roadmap, Memorandum for Distribution* (November 2009)
- Fukumori, I., D. Menemenlis, and T. Lee (2006), A near-uniform basin-wide sea level fluctuation of the Mediterranean Sea, *J. Phys. Oceanogr.*, 37, 338-358.
- Han, W., et al., 2010: Patterns of Indian Ocean sea level change in a warming climate, *Nature Geoscience*, 3, 546-550, DOI:10.1038/NGEO901
- Leuliette, E. W. and J. K. Willis (2011). "Balancing the Sea Level Budget." *Oceanography* 24(2): 122-129.
- Nicholls, R.J. and A. Cazenave (2009), *Sea-Level Rise and Its Impact on Coastal Zones*, *Science*, 328, 5985, 1517-1520, DOI: 10.1126/science.1185782
- NRC (2011), *National Security Implications of Climate Change for U.S. Naval Forces*, National Academies Press.
- Pacific Institute Report commissioned by the Ocean Protection Council, the Public Interest Research Program of the California Energy Commission, and the California Department of Transportation (2009), "The Impacts of Sea Level Rise on the California Coast", http://www.pacinst.org/reports/sea_level_rise/index.htm
- Perette, M., R. Riva, F. Landerer, K. Frieler, and M. Meinhausen (2011), Probabilistic projections of sea-level change along the world's coastlines, submitted.
- Rignot, E. & Thomas, R. Mass balance of polar ice sheets *Science*, AMER ASSOC ADVANCEMENT SCIENCE, 2002, 297, 1502-1506
- Riva, R. E. M., J. L. Bamber, D. A. Lavallée, and B. Wouters (2010), Sea level finger print of continental water and ice mass change from GRACE, *Geophys. Res. Lett.*, 37, L19605, doi:10.1029/2010GL044770

- Swenson, S., P. J. F. Yeh, et al. (2006). "A comparison of terrestrial water storage variations from GRACE with in situ measurements from Illinois." *Geophysical Research Letters* 33(16).
- Syed, T. H., J. S. Famiglietti, et al. (2008). "Analysis of terrestrial water storage changes from GRACE and GLDAS." *Water Resources Research* 44(2).
- Valiela, I., Bowen, J.L., York, J.K., 2001. *Mangrove Forests: One of the world's threatened major tropical environments*. *Bioscience*, Vol. 51, No. 10, pp. 807-815.
- Velicogna, I. (2009). "Increasing rates of ice mass loss from the Greenland and Antarctic ice sheets revealed by GRACE." *Geophysical Research Letters* 36.
- Wu, X., M. B. Heflin, E. R. Ivins, and I. Fukumori, Seasonal and interannual global surface mass variations from multisatellite geodetic data, *J. Geophys. Res.*, 111, B09401, doi:10.1029/2005JB004100, 2006.
- Wu, X., M. B. Heflin, H. Schotman, B. L. A. Vermeersen, D. Dong, R. S. Gross, E. R. Ivins, A. W. Moore & S. E. Owen, Simultaneous estimation of global present-day water transport and glacial isostatic adjustment, *Nature Geosci.*, article, 3, 642-646, 2010.